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Dark Sector Physics

J. Jaeckel

S. Abel, M. Cicoli, M. Goodsell,
V. Khoze, J. Redondo, A. Ringwald
Special Thanks also to
the Physics Beyond Colliders Study Group,
Claude Vallee and Mike Lamont

Where we want to go… a mythical story

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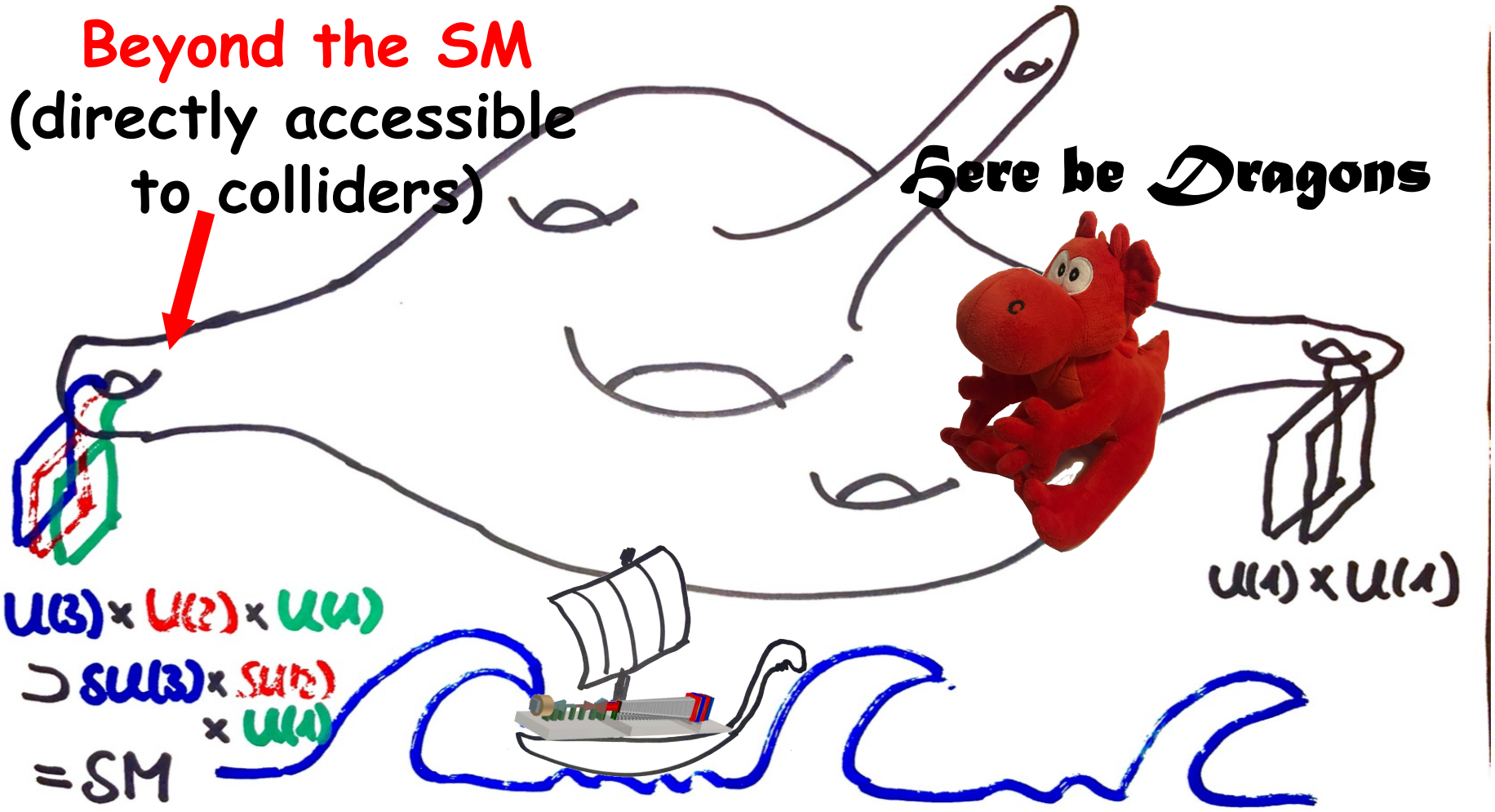

Motivation for a dark sector I: The Obvious

Inventory of the (mostly INVISIBLE) Universe

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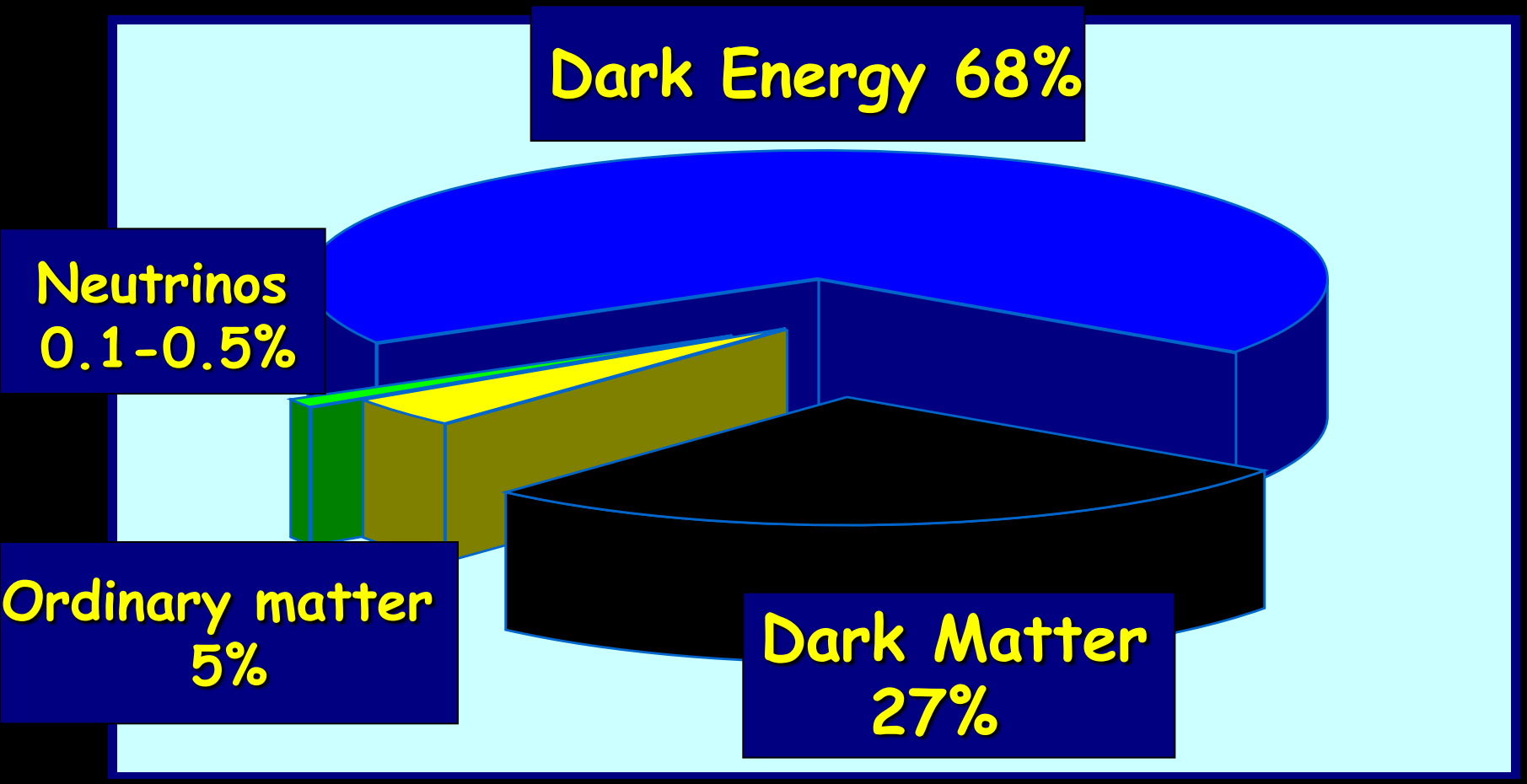

Inventory of the (mostly INVISIBLE) Universe

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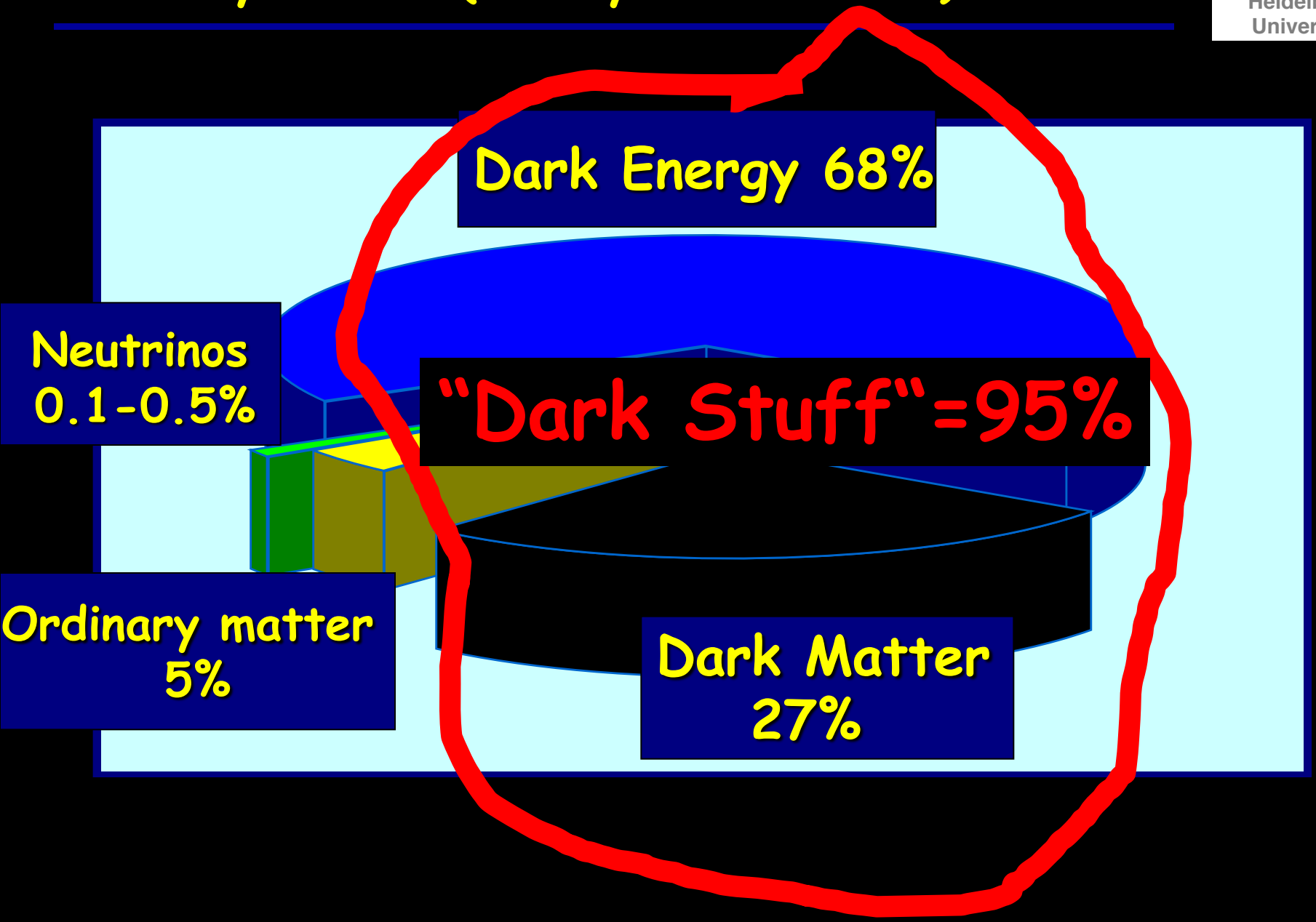

Working Definition:

Dark Sector

=

Very Weakly coupled to SM

Exploring is (at least) 2 dimensional

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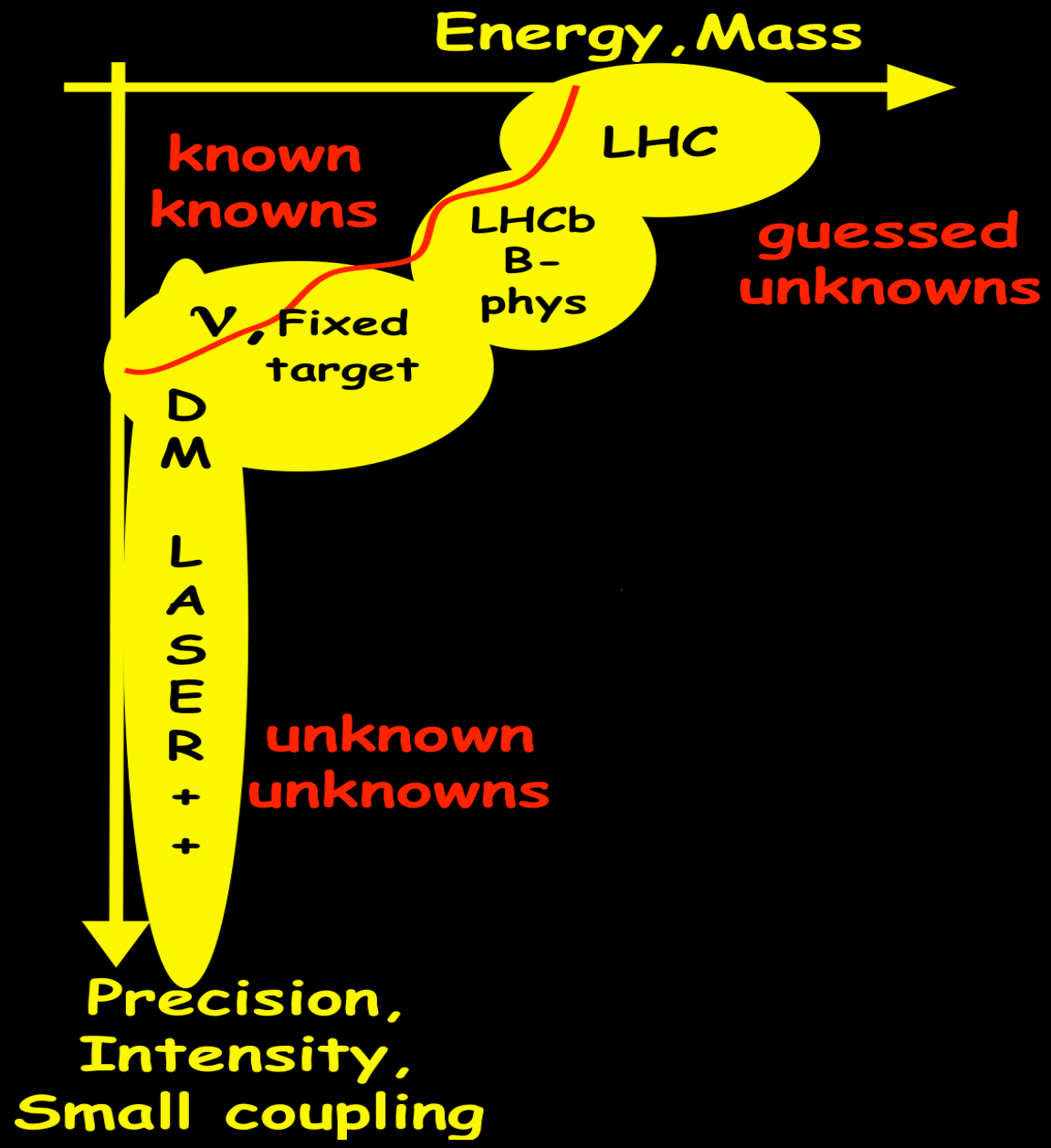

Exploring is (at least) 2 dimensional

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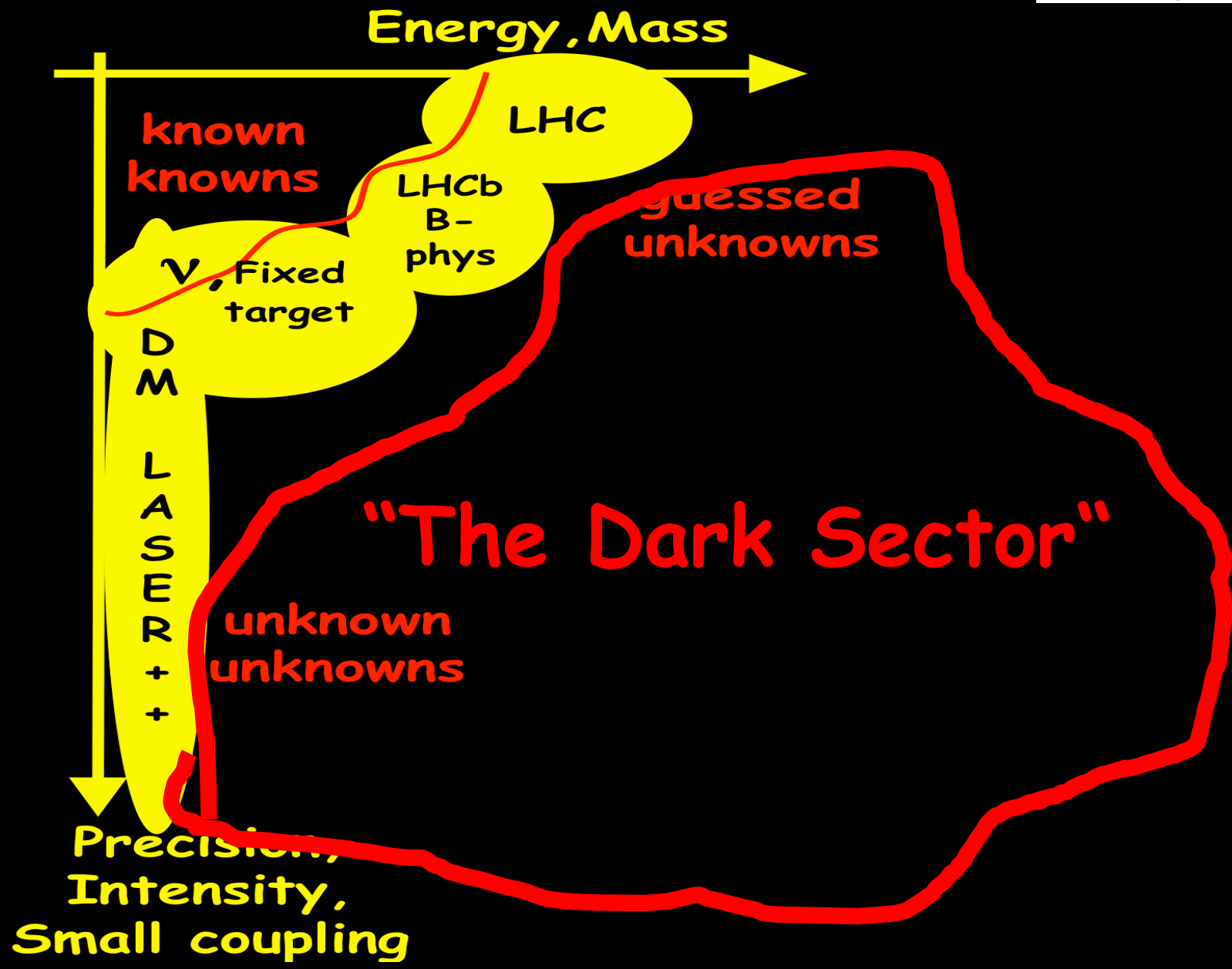

Experimental landscape (PBC)

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Energy, Mass

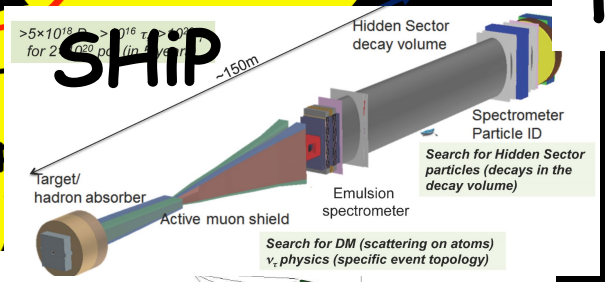
known knowns

LHC

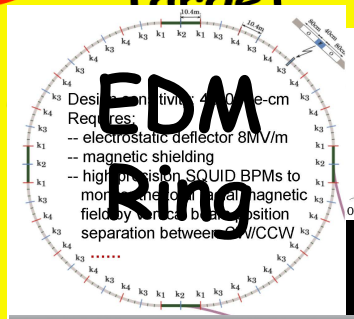
ν, Fixed target

TauFV

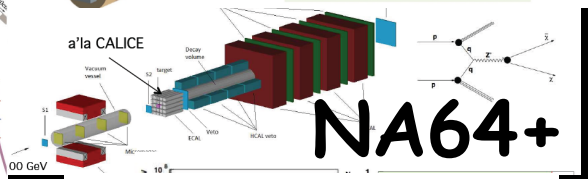
SHiP



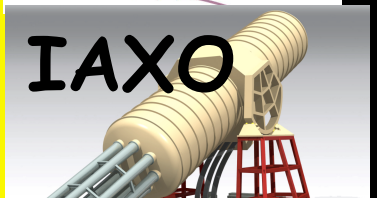
EDM Ring



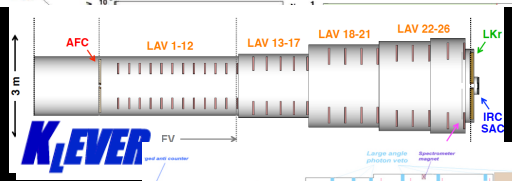
NA64+



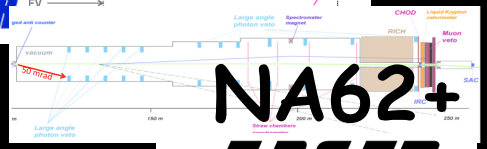
IAXO



KLEVER

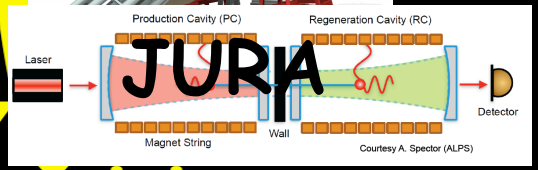


NA62+

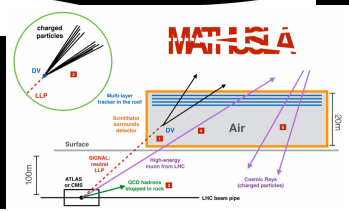


FASER

JURA



MATHUSLA



Codex-b

Precision, Intensity, Small coupling

In "linear" scale

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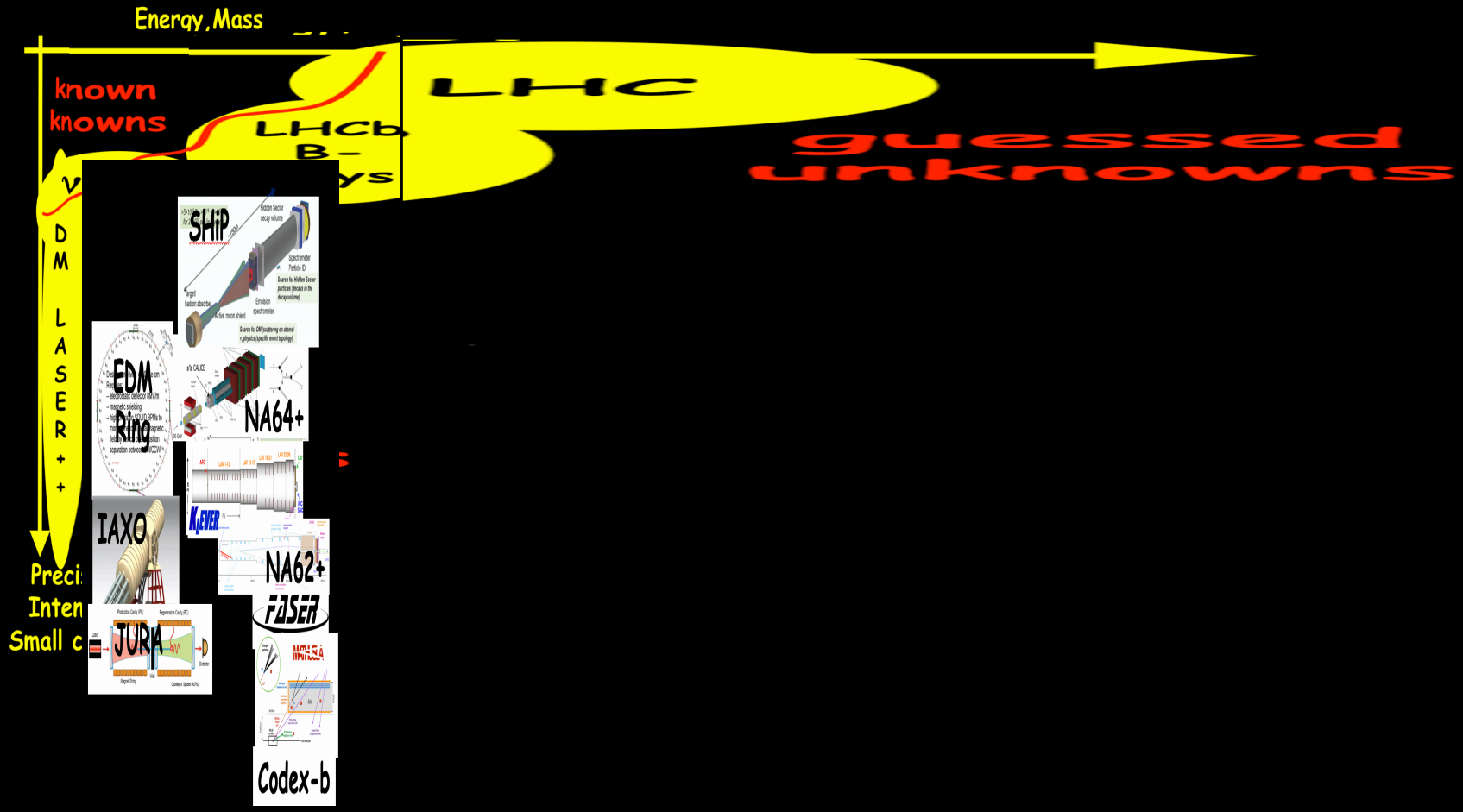

In "linear" scale

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We are mostly exploring the low mass region

Can Dark Sector particles be light?

In "linear" scale

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We are mostly exploring the low mass region

Can Dark Sector particles be light?

Probably, Yes!

Motivation for a dark sector II: Model Examples

An example:
Axions,
axion like particles,
general pseudo-Goldstone bosons

This is only an example
Many more cool and interesting models to test!!!
see, e.g., 1901.09966

The example:
Axions,
axion like particles,
general pseudo-Goldstone bosons

On the Elliptic Calabi-Yau Fourfold with Maximal $h^{1,1}$

Yi-Nan Wang[a]

Abstract: In this paper, we explicitly construct the smooth compact base threefold for the elliptic Calabi-Yau fourfold with the largest known $h^{1,1} = 303\,148$. It is generated by blowing up a smooth toric "seed" base threefold with (E_8, E_8, E_8) collisions. The 4d F-theory compactification model over it has the largest geometric gauge group, $E_8^{2\,561} \times F_4^{7\,576} \times G_2^{20\,168} \times SU(2)^{30\,200}$, and the largest number of axions, 181 820, in the known 4d $\mathcal{N} = 1$ supergravity landscape. We also prove that there are at least $1100^{15\,048} \approx 7.5 \times 10^{45\,766}$ different flop phases of this base threefold. Moreover, we find that many other base threefolds with large $h^{1,1}$ in the 4d F-theory landscape can be constructed in a similar way as well.

https://arxiv.org/pdf/2001.07258.pdf

What is a Goldstone Boson?

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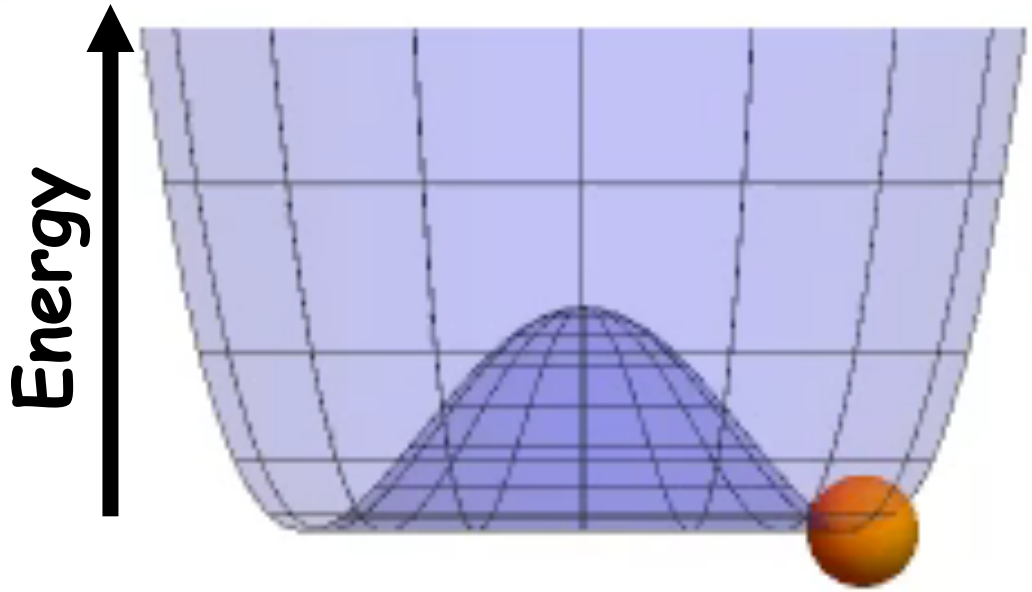
- Let us start with a U(1)/rotation symmetric potential



field excitation

angular excitation

➔ If you move along the minimum, it costs no energy to move around

➔ Particle is massless

What is a pseudo-Goldstone Boson?

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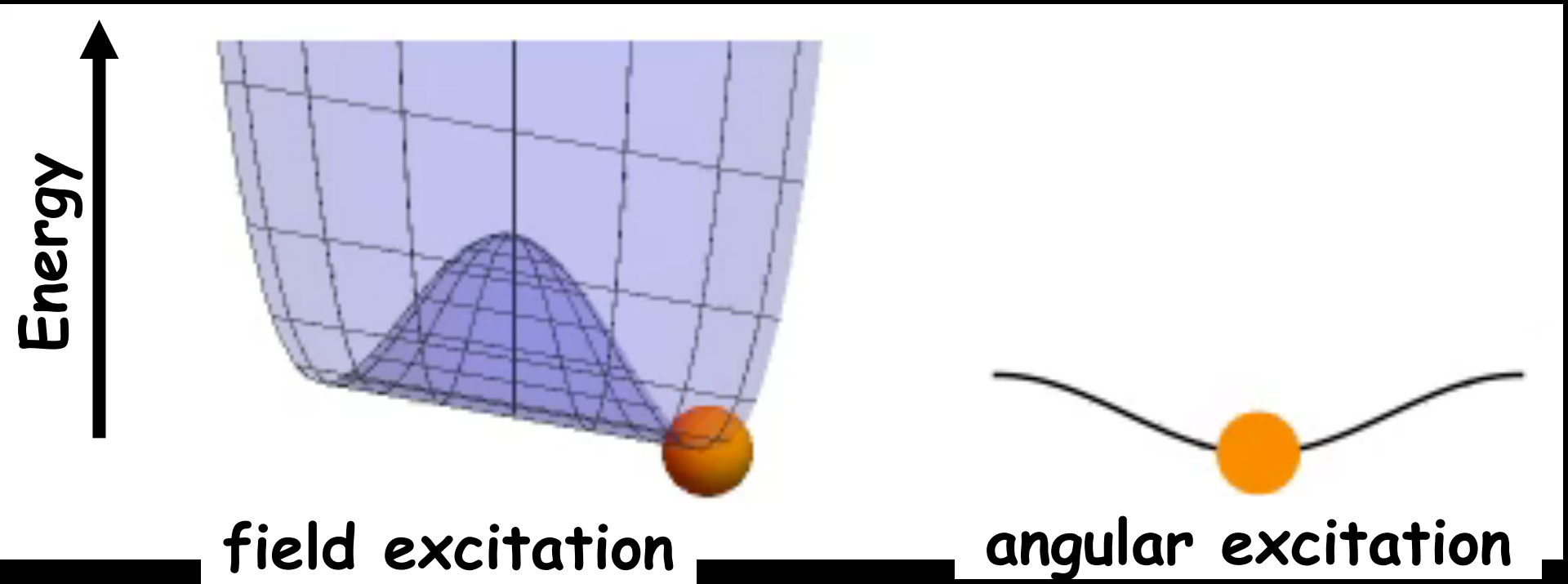
- Add a small breaking of U(1)/rotation symmetry



→ If you move along the minimum, it costs a little bit of energy

→ Particle has a small mass

What is a pseudo-Goldstone Boson?

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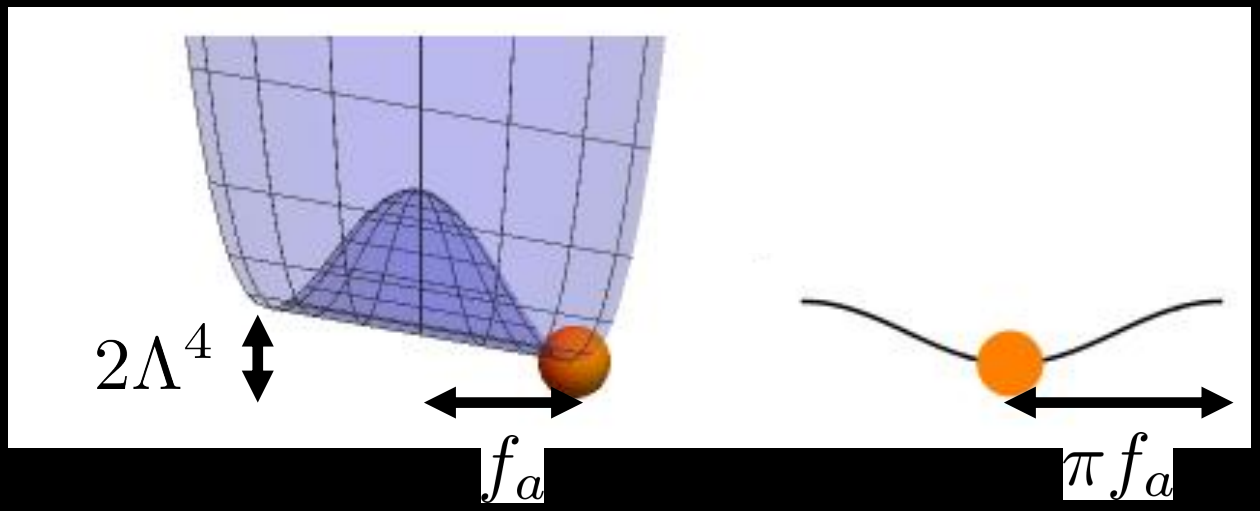
- Add a small breaking of U(1)/rotation symmetry



$$V(a) = \Lambda^4 \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

very small

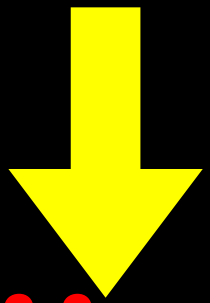
small

$$\text{mass}^2 = m_X^2 = V''(0) = \frac{\Lambda^4}{f_a^2}$$

large

Message:

Large scale f_a



Small mass

Coupling to $F\tilde{F}$ ($G\tilde{G}$ analog)

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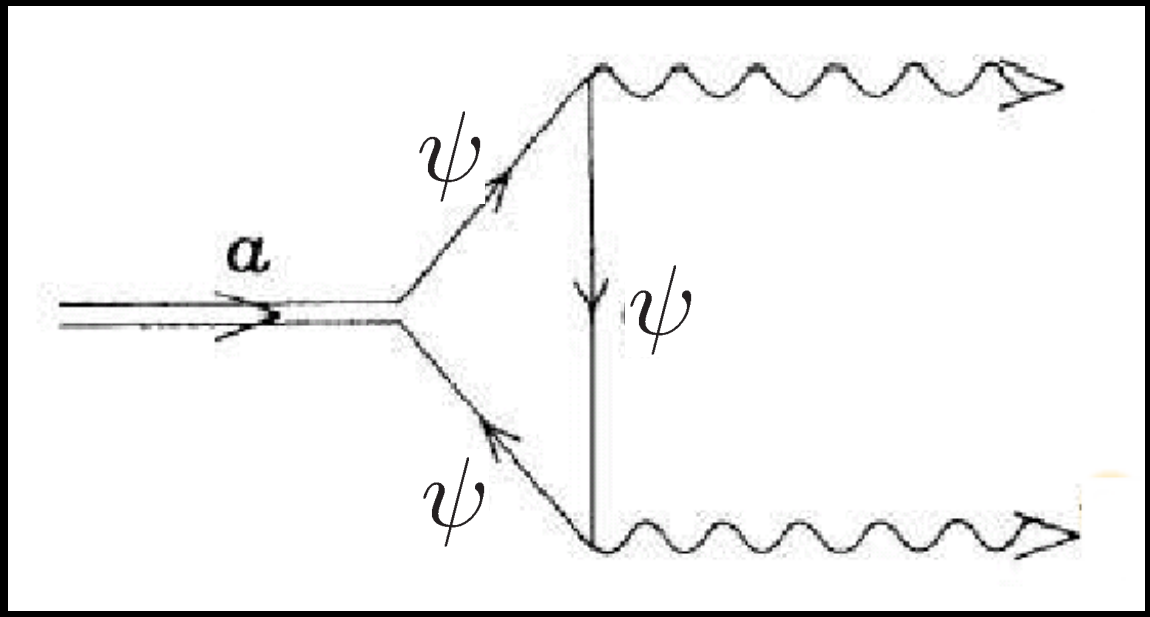
- A diagram



- And a dimensional argument both give:

$$g \sim \frac{1}{\mathrm{m}_\psi} \sim \frac{1}{f_a}$$

Couplings fixed by scale of symmetry breaking: f_a

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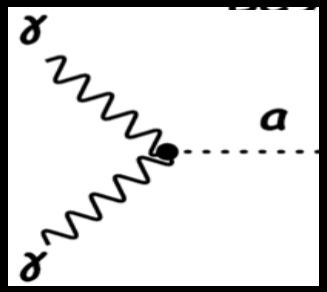
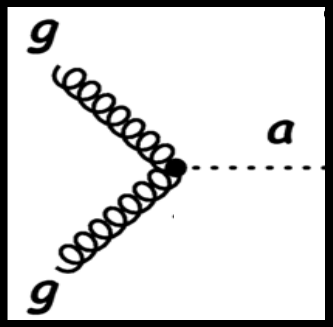
- **Photon coupling**



$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

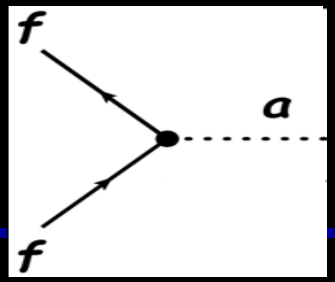
- **Gluon coupling**



$$\mathcal{L} \supset \frac{1}{4} g_{agg} a G^{\mu} \tilde{G}_{\mu\nu}$$

$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

- **Fermion couplings**



$$\mathcal{L} \supset g_{a\psi\psi} a \bar{\psi} \gamma^5 \psi$$

$$g_{a\psi\psi} \sim \frac{m_{\psi}}{f_a}$$

Couplings fixed by scale of symmetry breaking: f_a

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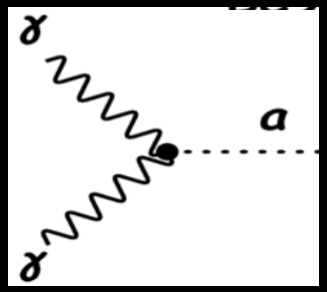
- **Photon coupling**



$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$

small → $g_{a\gamma\gamma} \sim \dfrac{\alpha}{4\pi f_a}$ ← large

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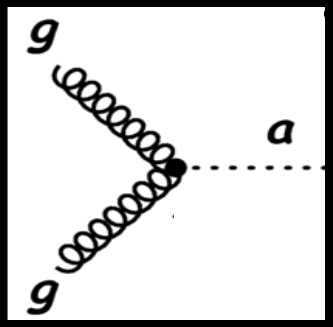

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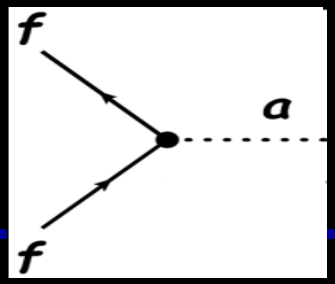

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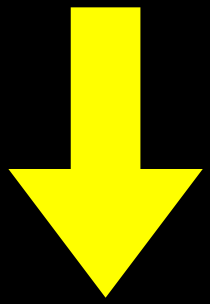
small → $g_{a\psi\psi} \sim \dfrac{m_{\psi}}{f_a}$ ← large

Message:

Large scale f_a



Small coupling

Target space

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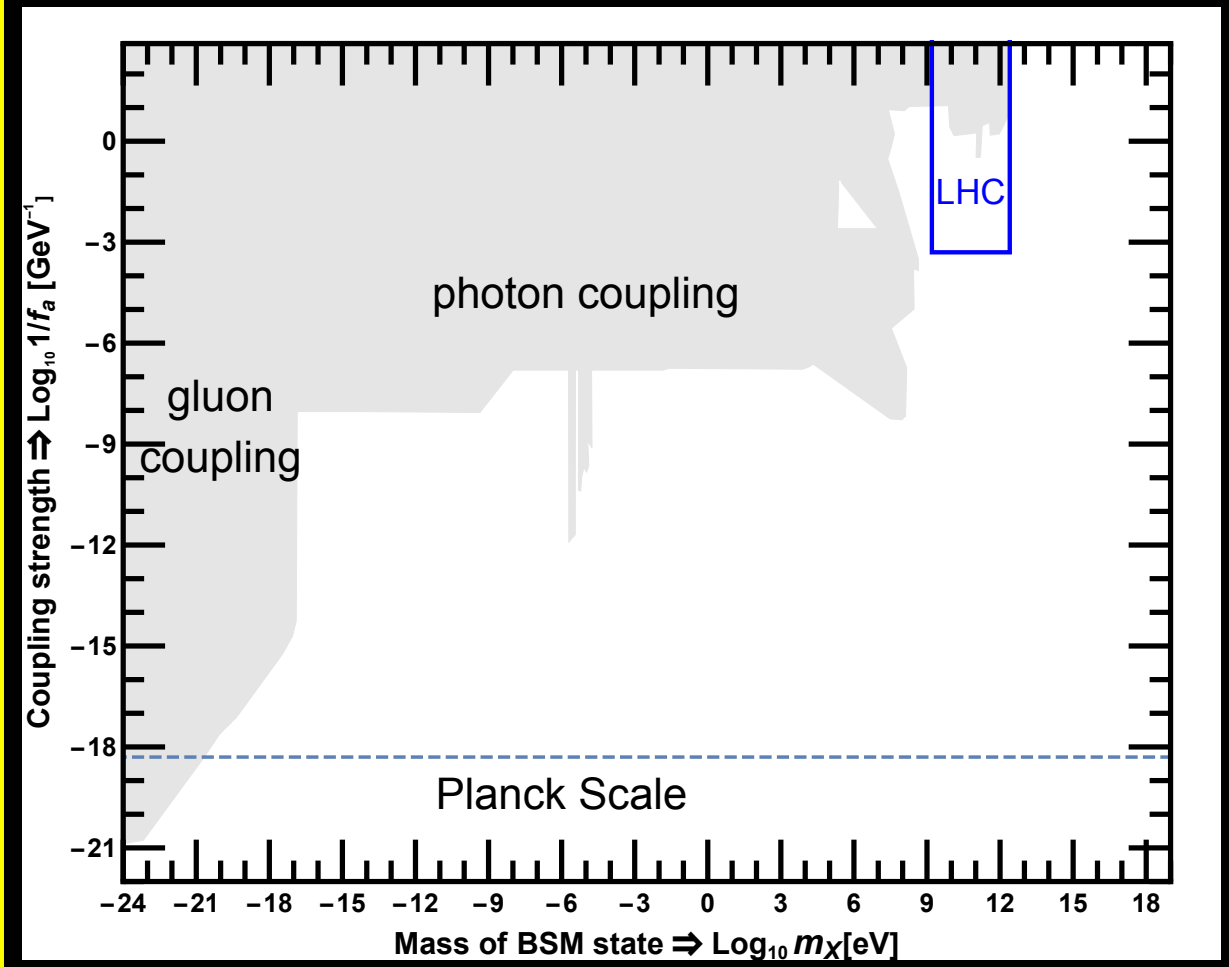
High mass



Small coupling

Target space

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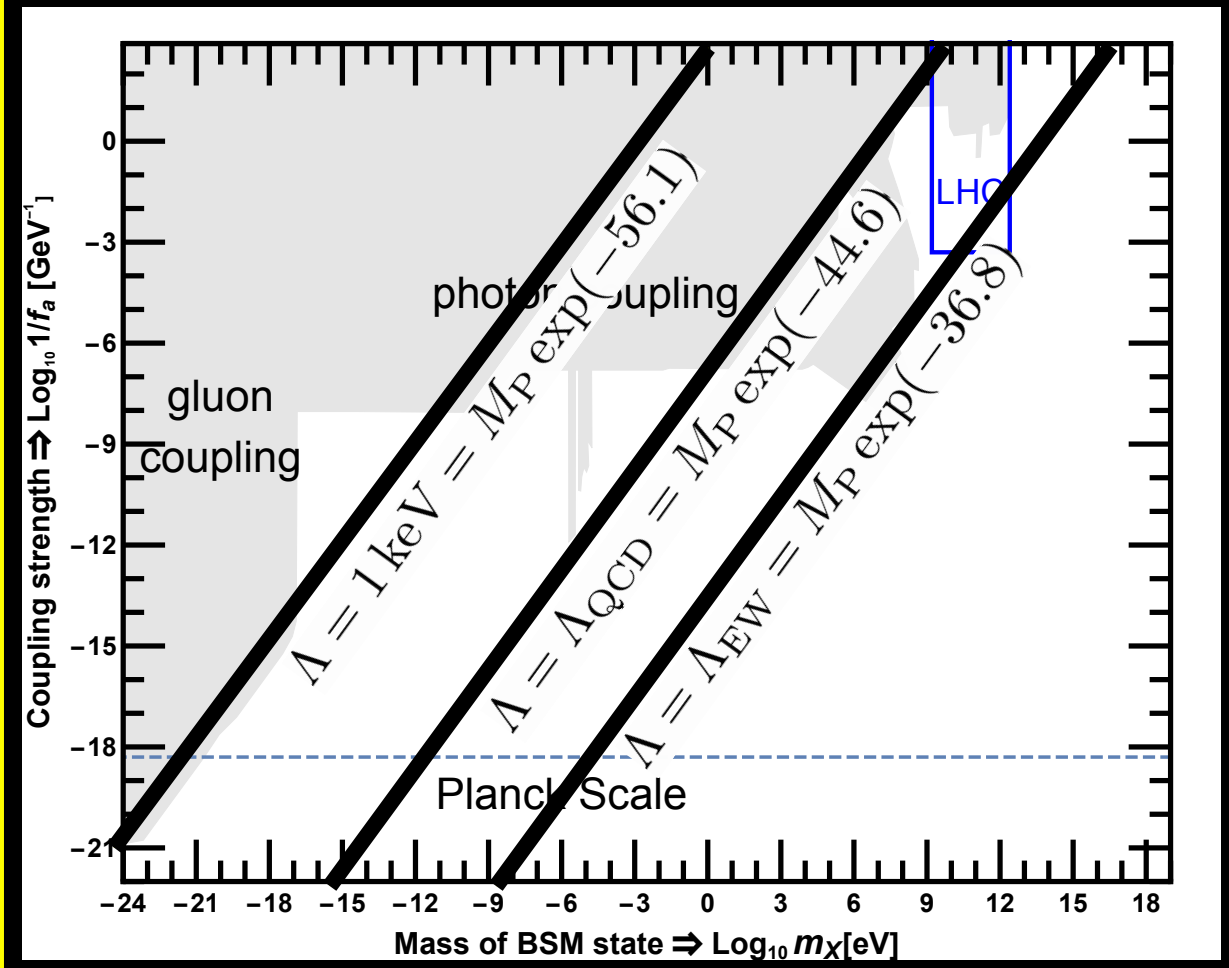
High mass



Small coupling

Motivation for a dark sector III: Observational Hints

Hidden/Dark Photons explain $(g-2)_\mu$

$(g-2)_\mu$

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- The SM predicts the value of the magnetic dipole moment of the muon:

$$\mu_\mu = \frac{e}{2m_\mu}(2 + (g-2)_\mu)$$

➔ Measure and calculate veeery precisely

$$\left(\frac{(g-2)_\mu}{2}\right)_{\text{exp}} = 11659209.1 \pm 6.3$$

→ To be halved by Fermilab exp.

$$\left(\frac{(g-2)_\mu}{2}\right)_{\text{th}} = 11659178.3 \pm 4.3$$

https://arxiv.org/pdf/1804.07409.pdf

→ improvement needed

➔ (3-4)σ discrepancy

Hidden Photon interactions

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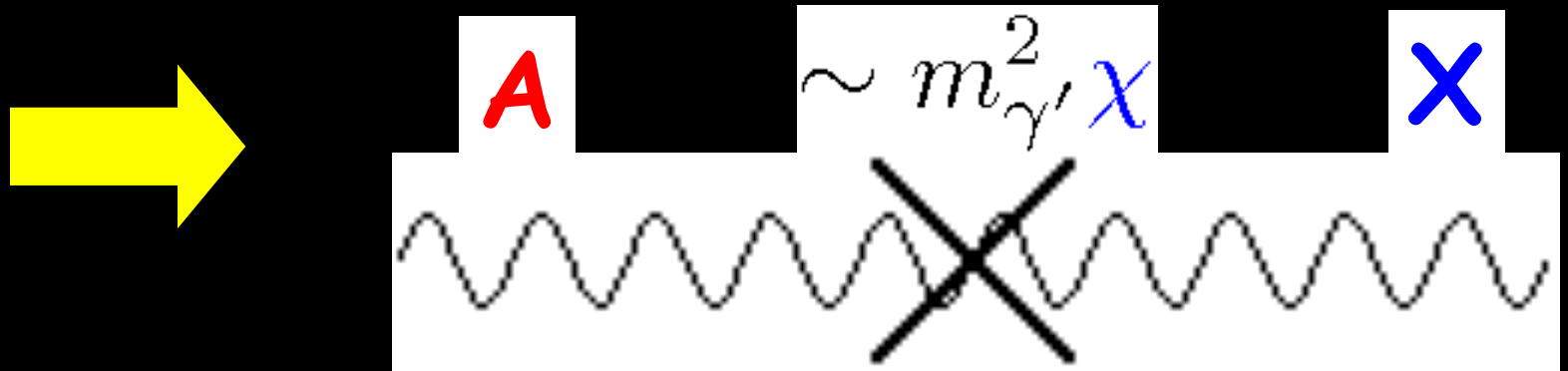
- Kinetic mixing

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \frac{\chi}{2} F^{\mu\nu} X_{\mu\nu}$$

„Our" U(1) | „Hidden" U(1) | Mixing

+ Mass $\mathcal{L}_{\text{mass}} = \frac{1}{2} m_{\gamma'}^2 X^\mu X_\mu$



Hidden/Dark Photon explanation

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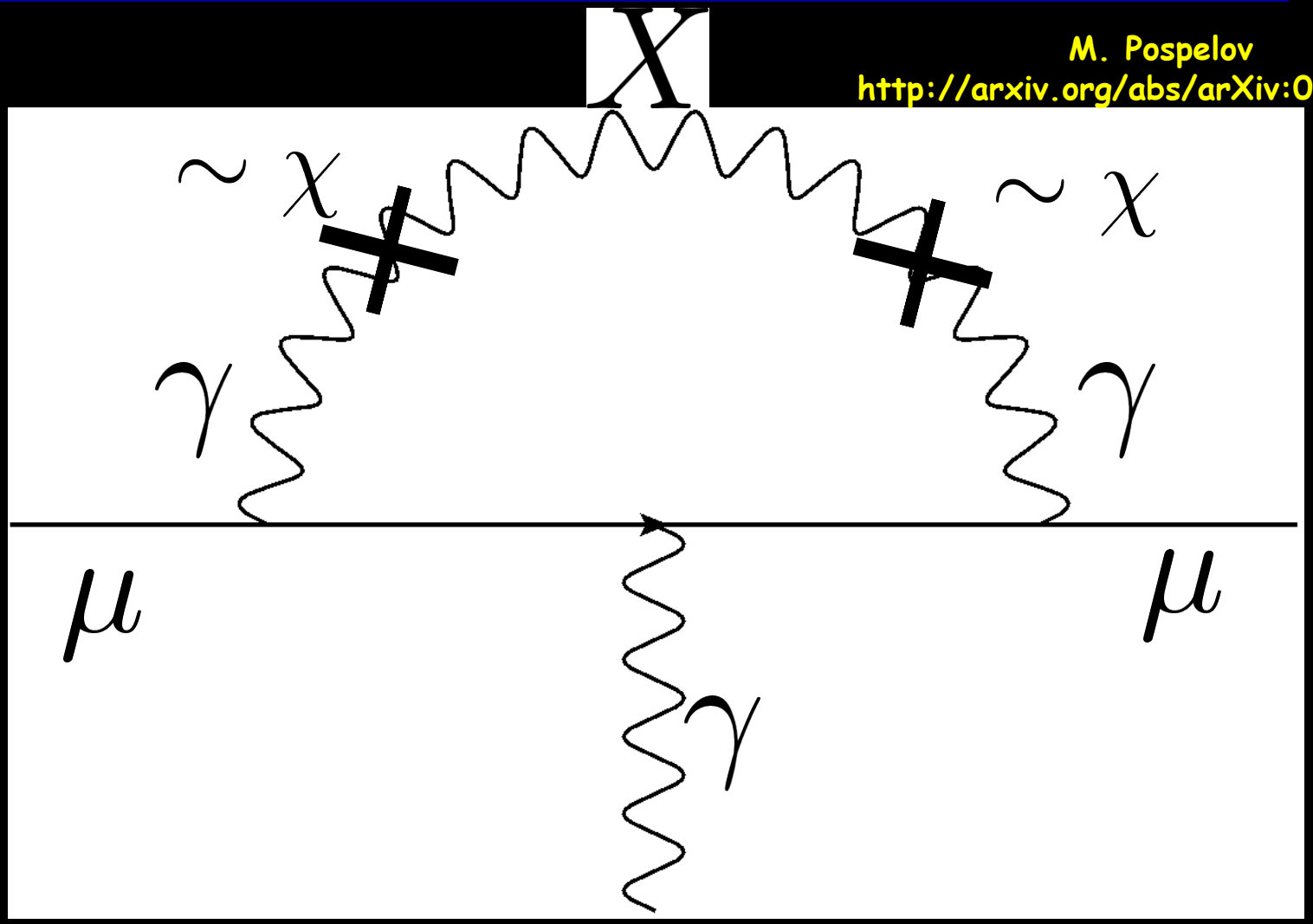
M. Pospelov
http://arxiv.org/abs/arXiv:0811.1030



Old Plot

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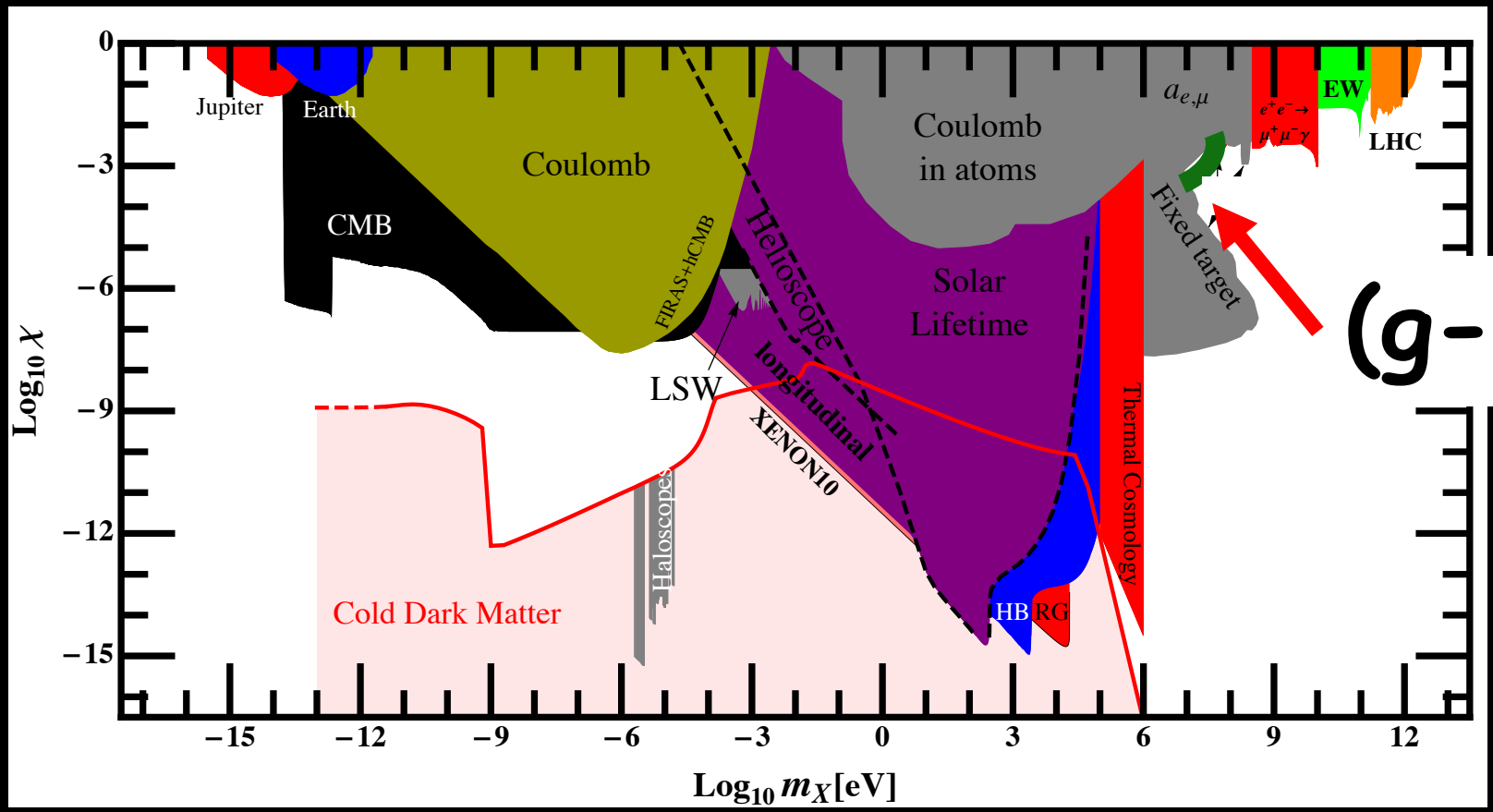

By now excluded

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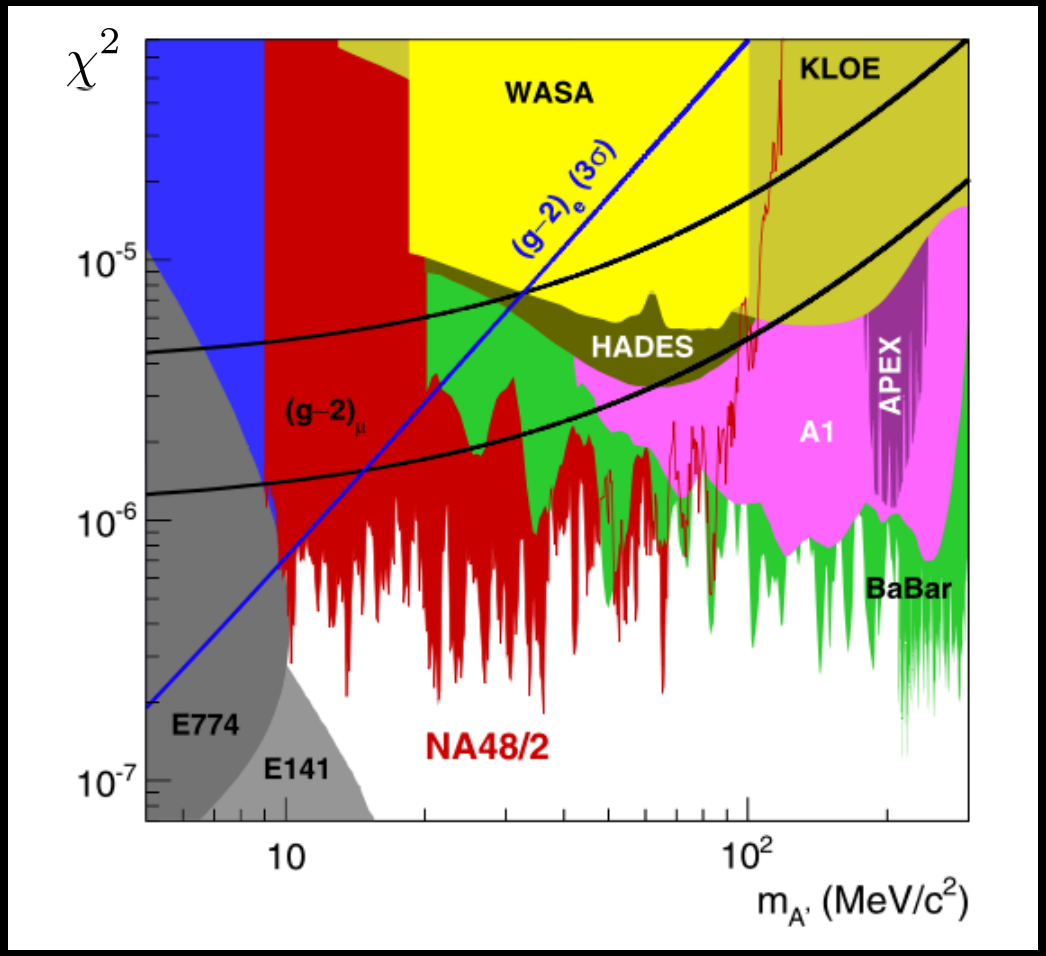

From NA48/2 collaboration
https://arxiv.org/pdf/1504.00607.pdf

With flavor dependent coupling still allowed

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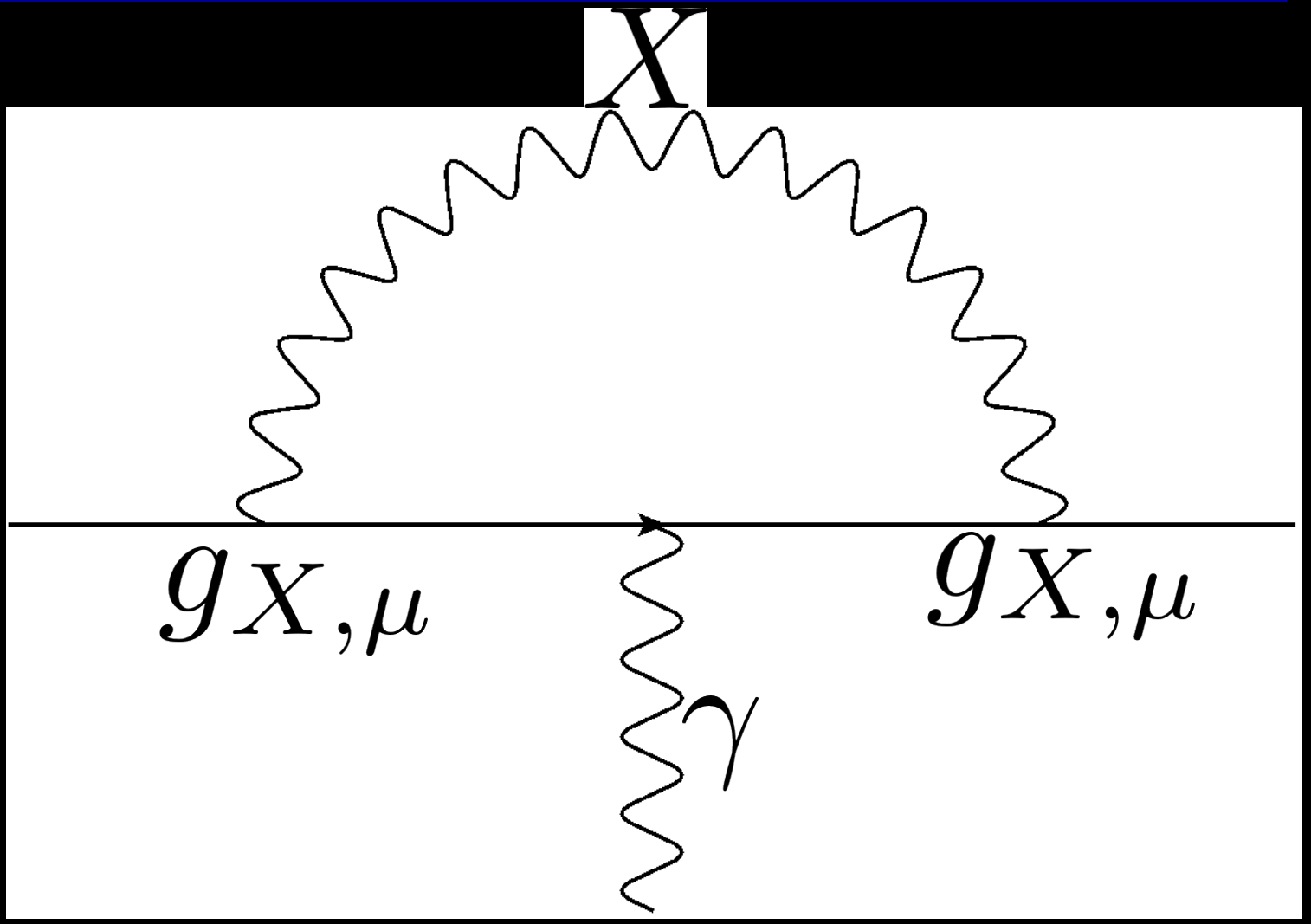

With flavor dependent coupling still allowed

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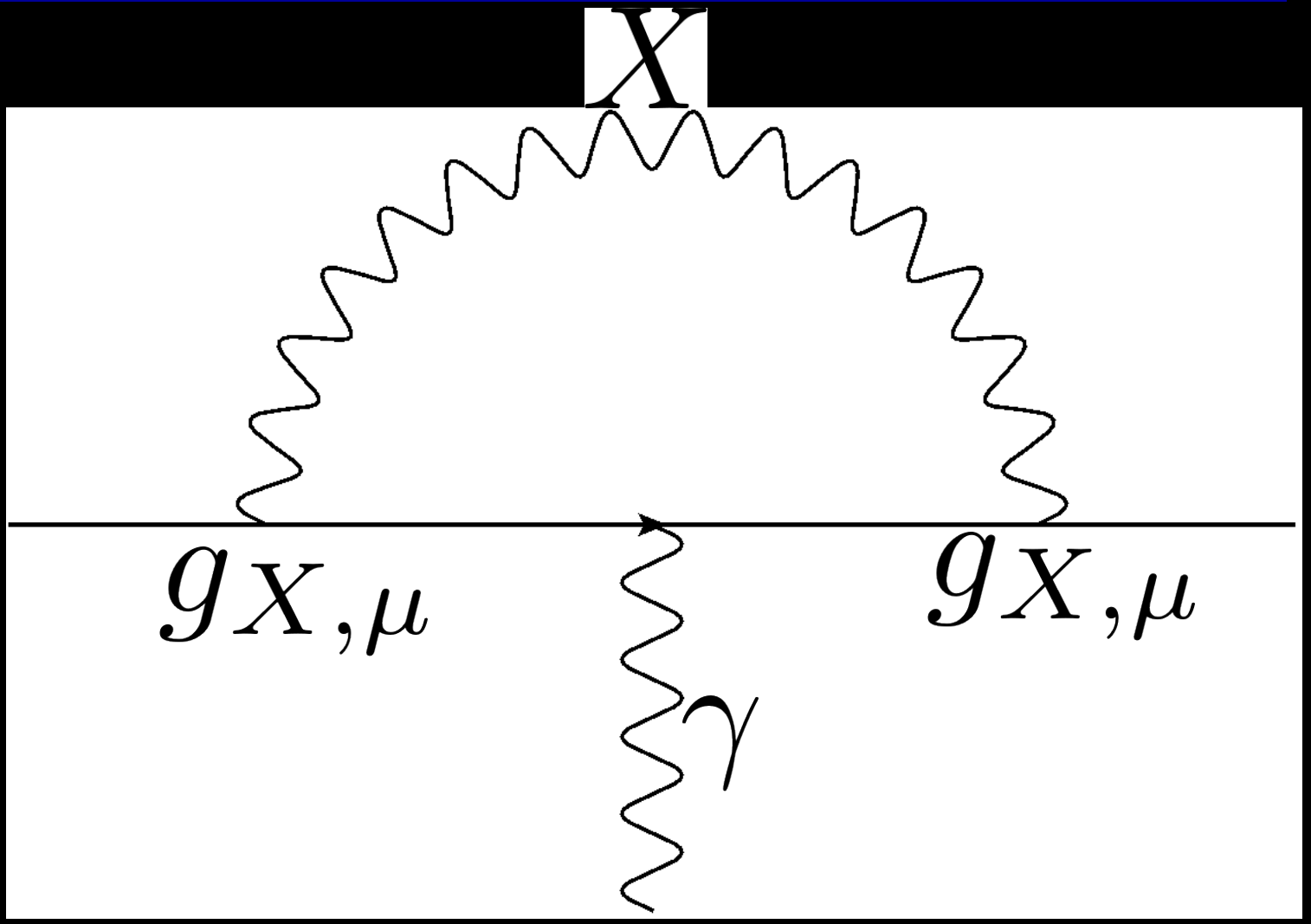

A similar diagram could work for an ALP!

Hidden/Dark photons as Dark Matter messengers

Messenging

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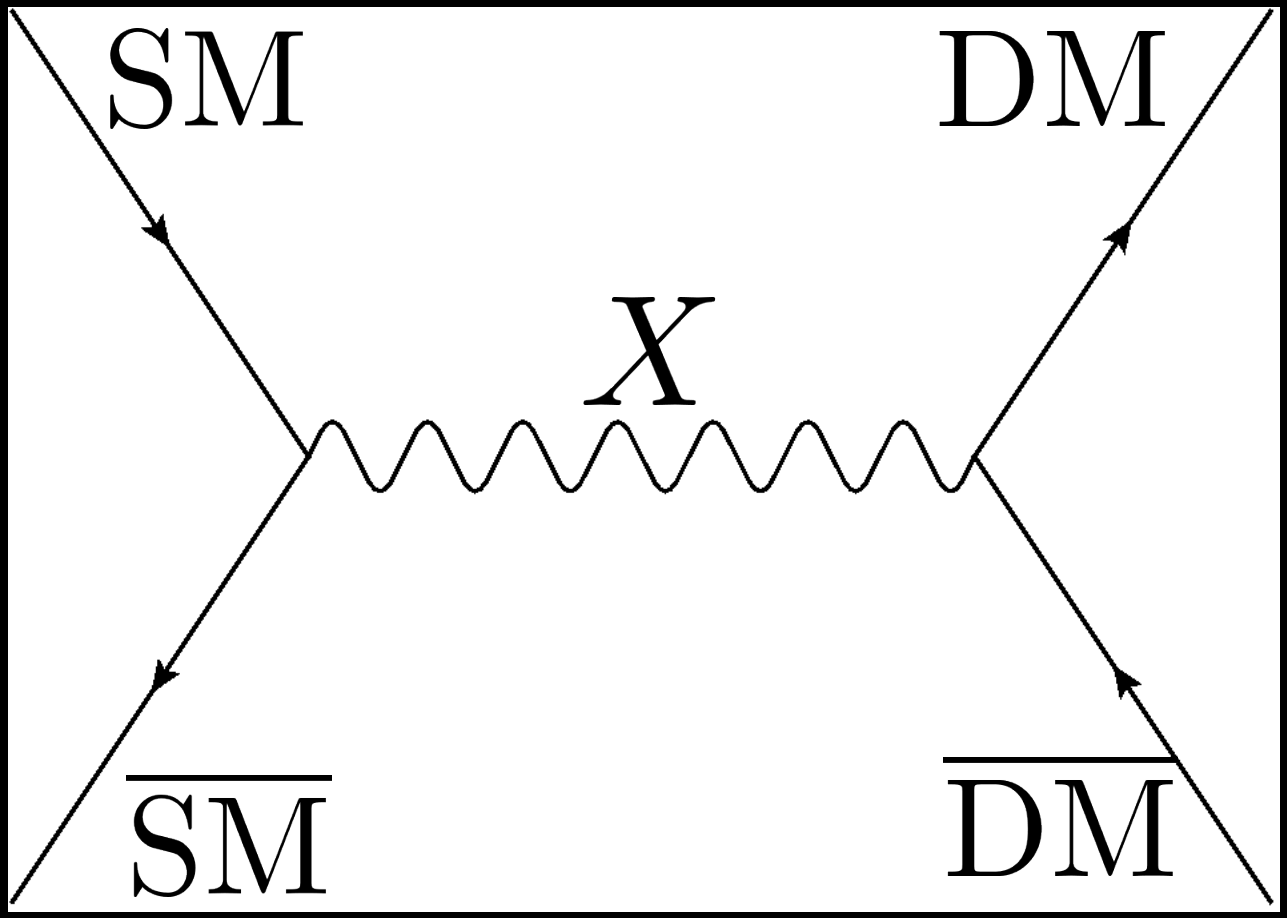

Thermal equilibrium

Indirect Detection

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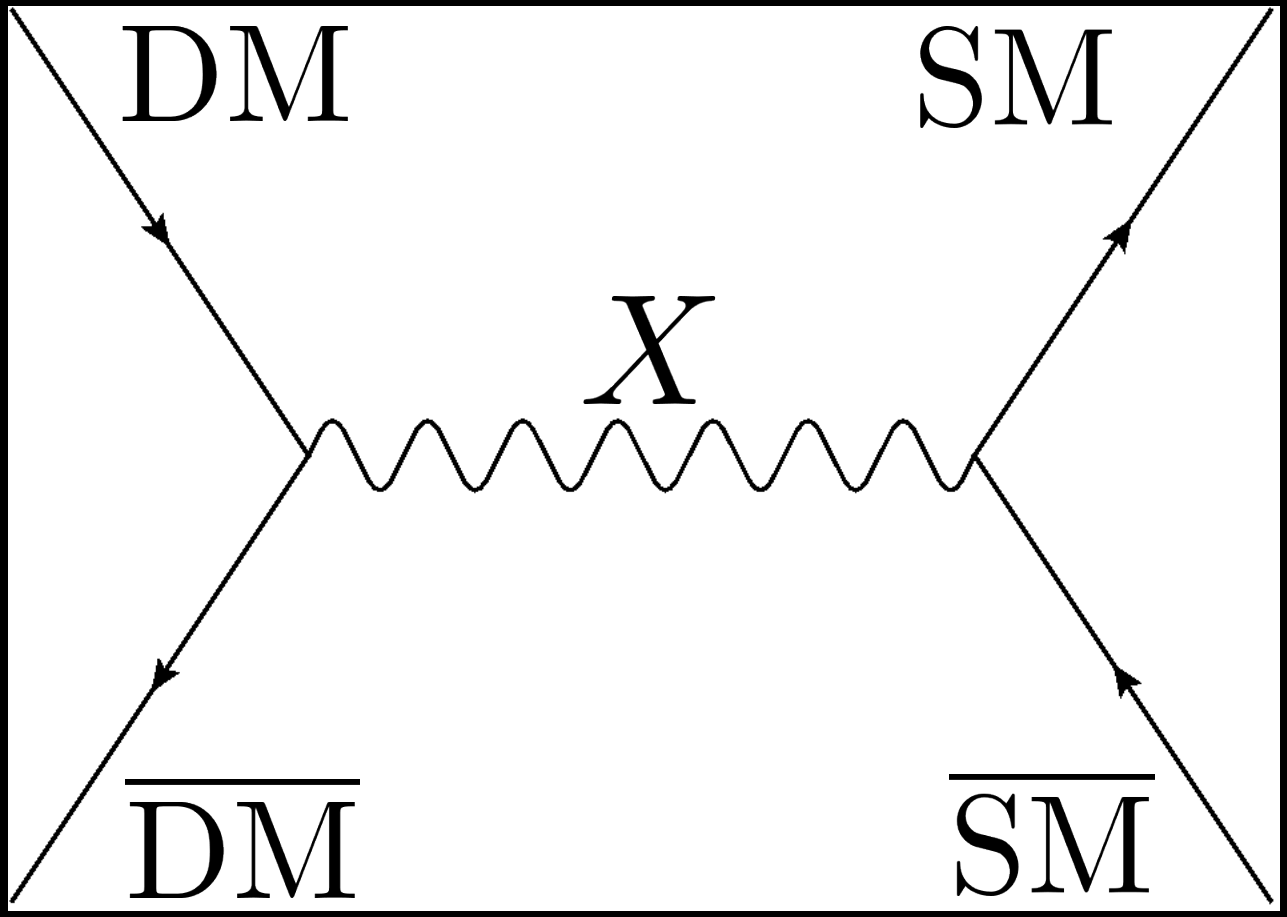
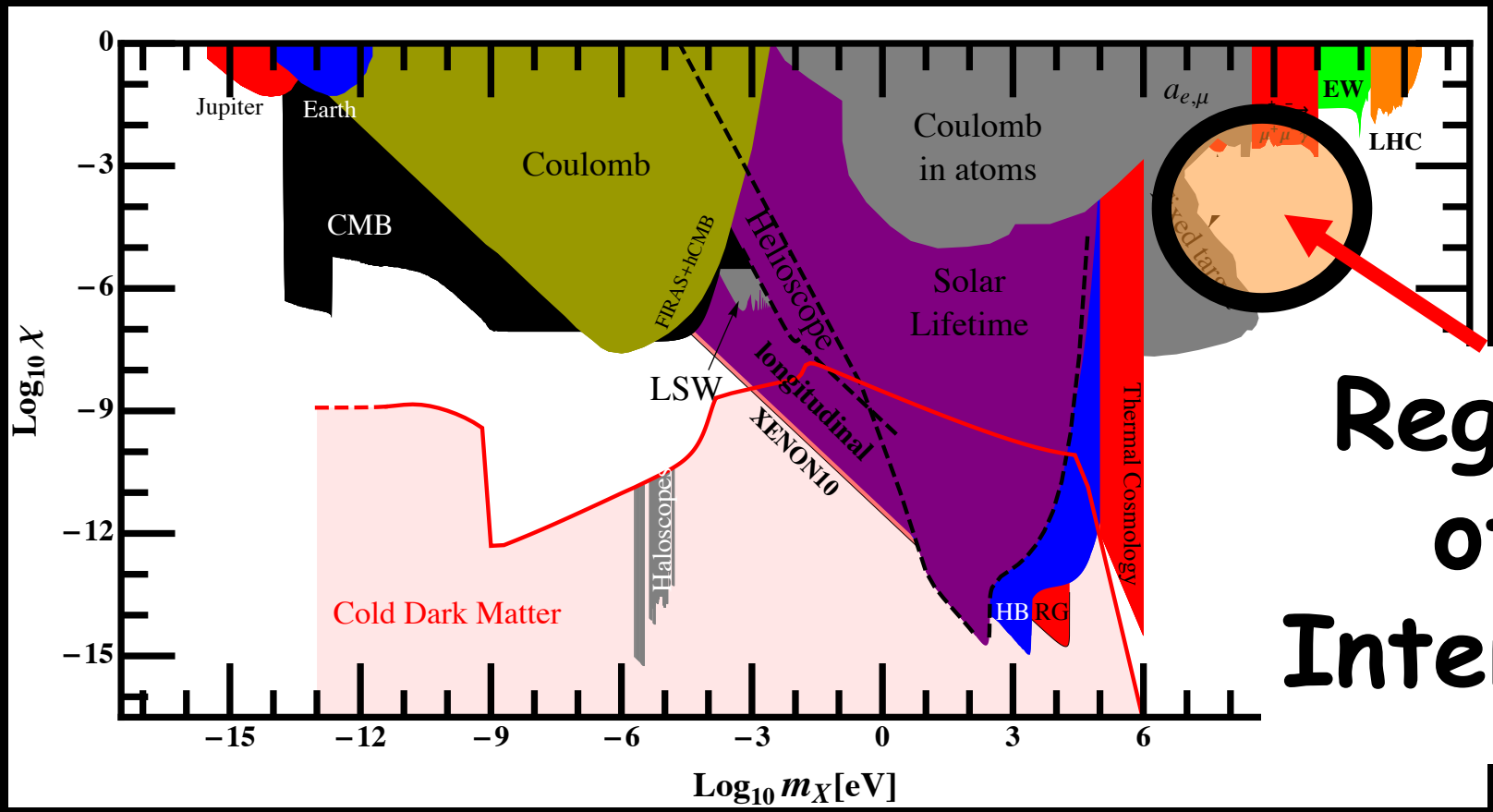


Dark Matter annihilation



Region of Interest

Motivation for a dark sector IV: Theory

Axion(-like particles)

String theory: Moduli and Axions

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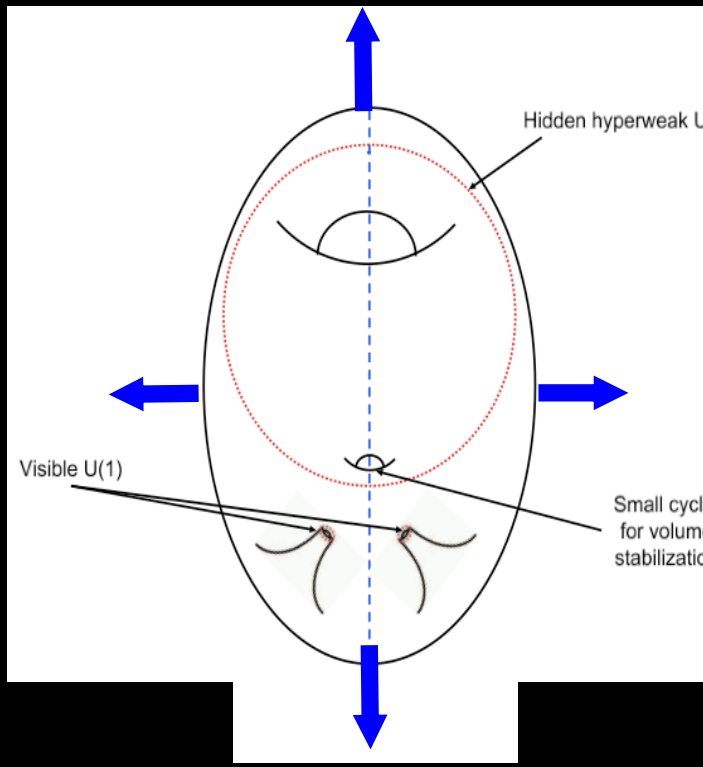
- String theory needs Extra Dimensions

Must compactify

- Shape and size deformations correspond to fields:
  Moduli and Axions
  Connected to the fundamental scale, here string scale



Axions and Moduli

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- Gauge field terms

$$\mathcal{L} = \frac{1}{g^2} F^2 + i\theta F\tilde{F}$$

If all couplings are set by field values (+SUSY)

$$\mathcal{L} = \mathrm{Re}[f(\Phi)] F^2 + \mathrm{Im}[f(\Phi)] F\tilde{F}$$

Scalar ALP/moduli coupling + pseudoscalar ALP coupling

Axions and Moduli

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- Gauge couplings always field dependent (no free coupling constants)

- Axions + Moduli always present in String theory

Masses and Couplings

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- "Axion scale" related to fundamental scale

$$f_a \sim \frac{M_P}{\text{Volume}^x} \sim M_s \left(\frac{M_s}{M_P}\right)^y$$

- If QCD axion: m_a fixed

- However, if not QCD axion

$$m_{\text{ALP}} \sim \frac{\Lambda^2}{f_a}$$

(nearly) arbitrary

Axion (like particles): Where are we?

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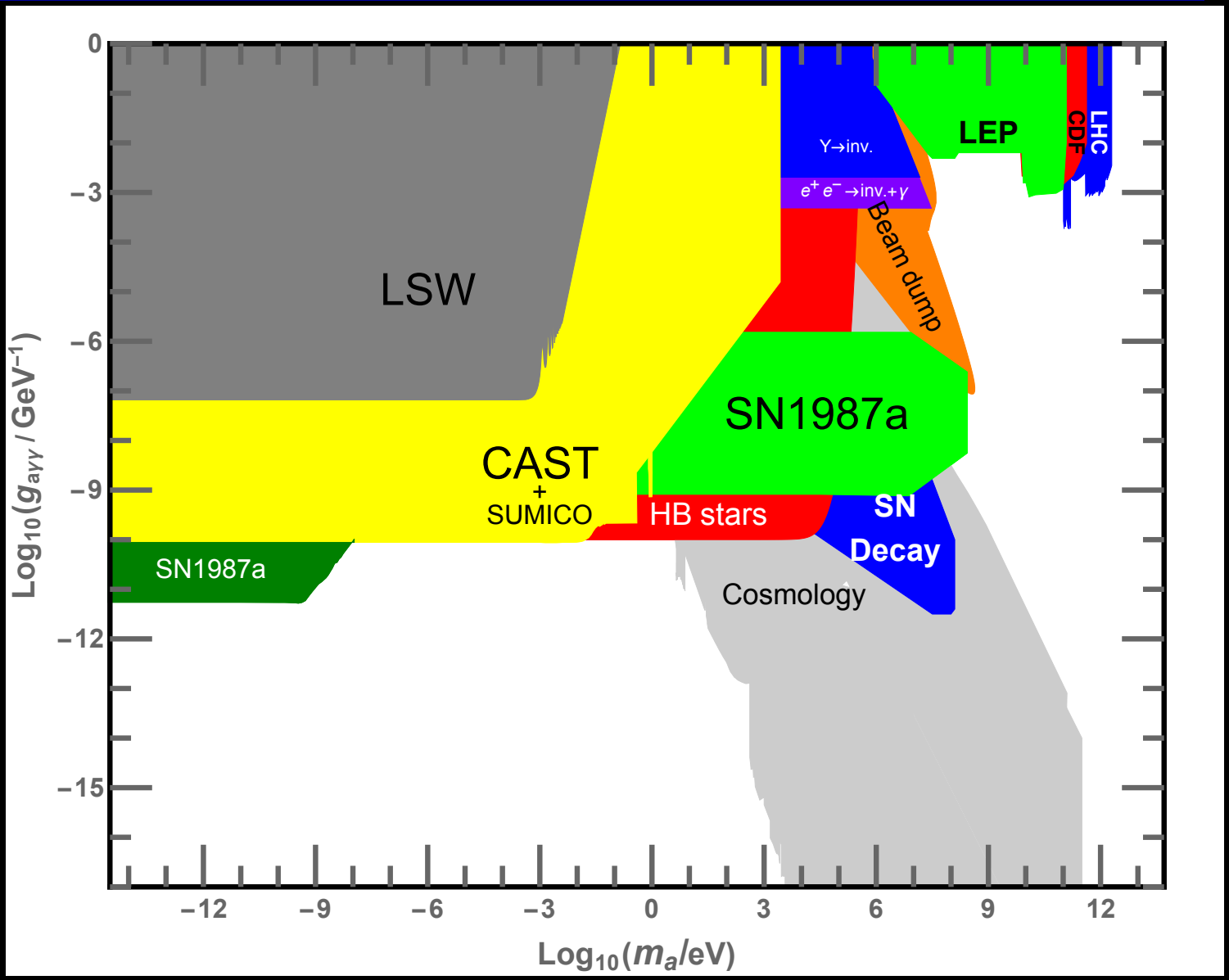

Axion (like particles): Where are we?

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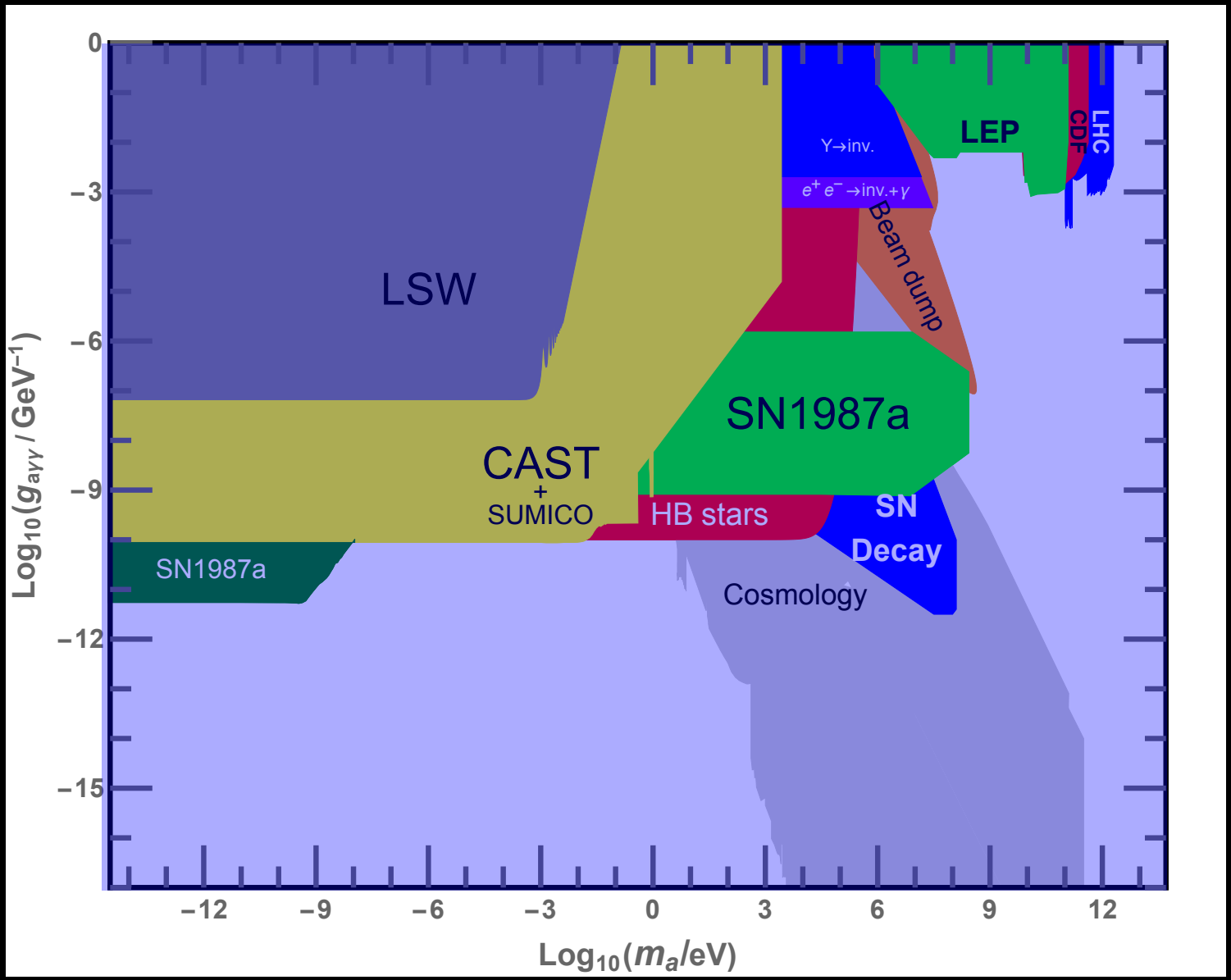

Hidden/Dark Photons

+

Hidden Matter

String theory likes extra gauge groups

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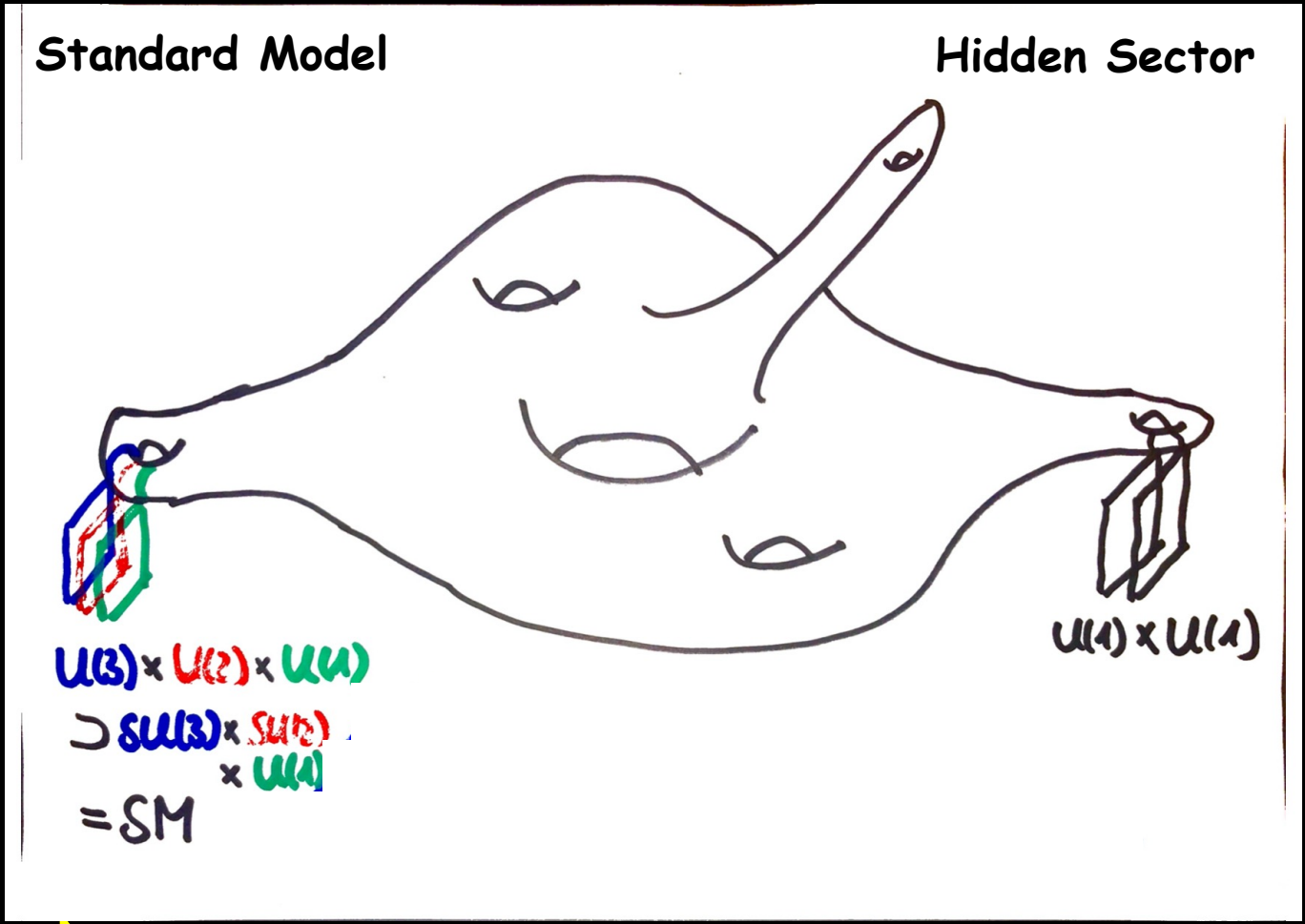

→ Many extra U(1)s!

→ Candidates for Hidden Photons

We want mixing and a mass!

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$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F^{\mu\nu}_{(\text{A})} F_{(\text{A})\mu\nu} - \frac{1}{4} F^{\mu\nu}_{(\text{B})} F_{(\text{B})\mu\nu} + \frac{\chi}{2} F^{\mu\nu}_{(\text{A})} F_{(\text{B})\mu\nu},$$

„Our" U(1)

„Hidden" U(1)

Mixing

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m^2_{\gamma'} X^\mu X_\mu$$

Hidden by distance/volume

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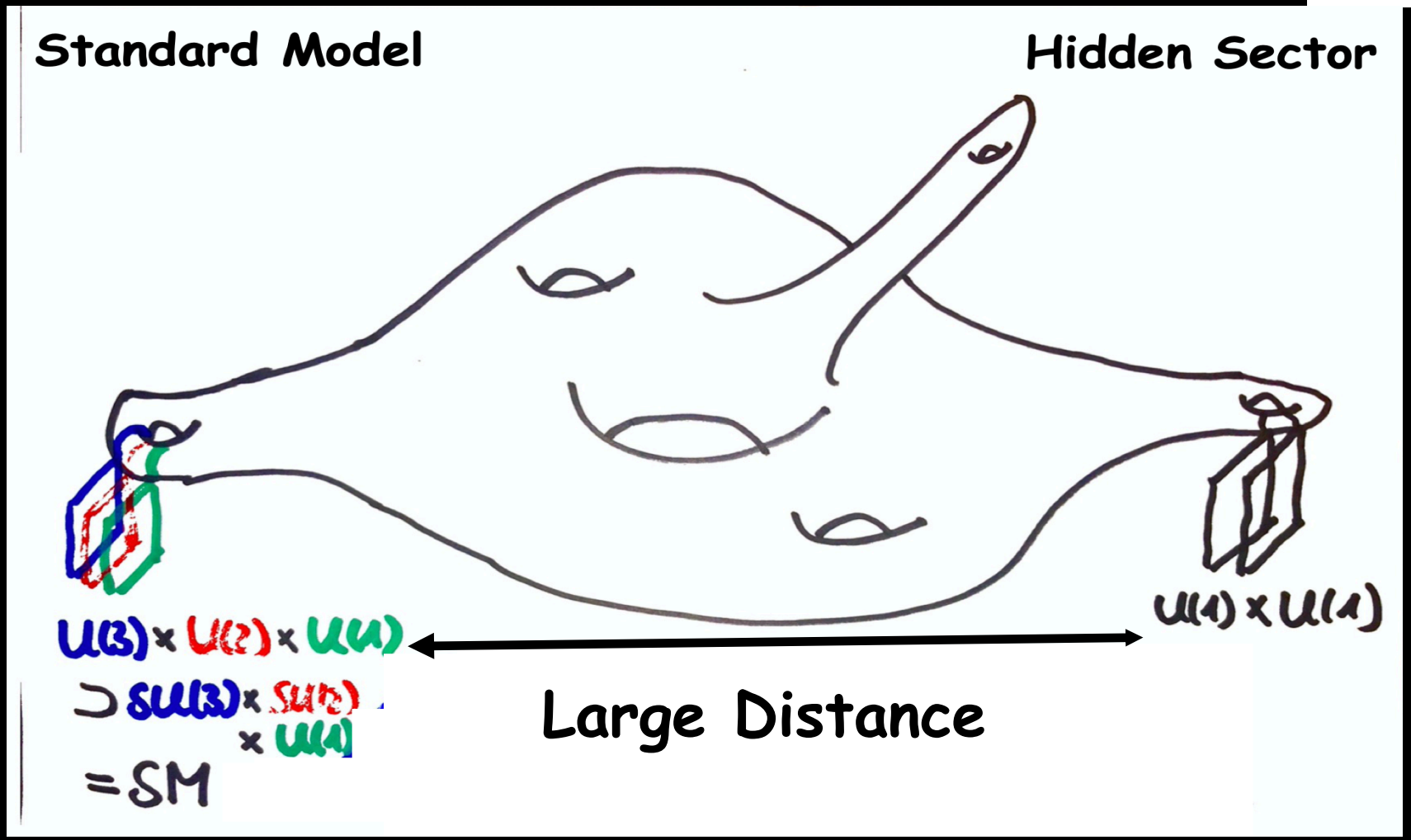

$$\chi \sim \frac{g_s}{8\pi} \frac{1}{Volume^x} \qquad g_{\rm hid} \sim 1$$

Hidden by weakness

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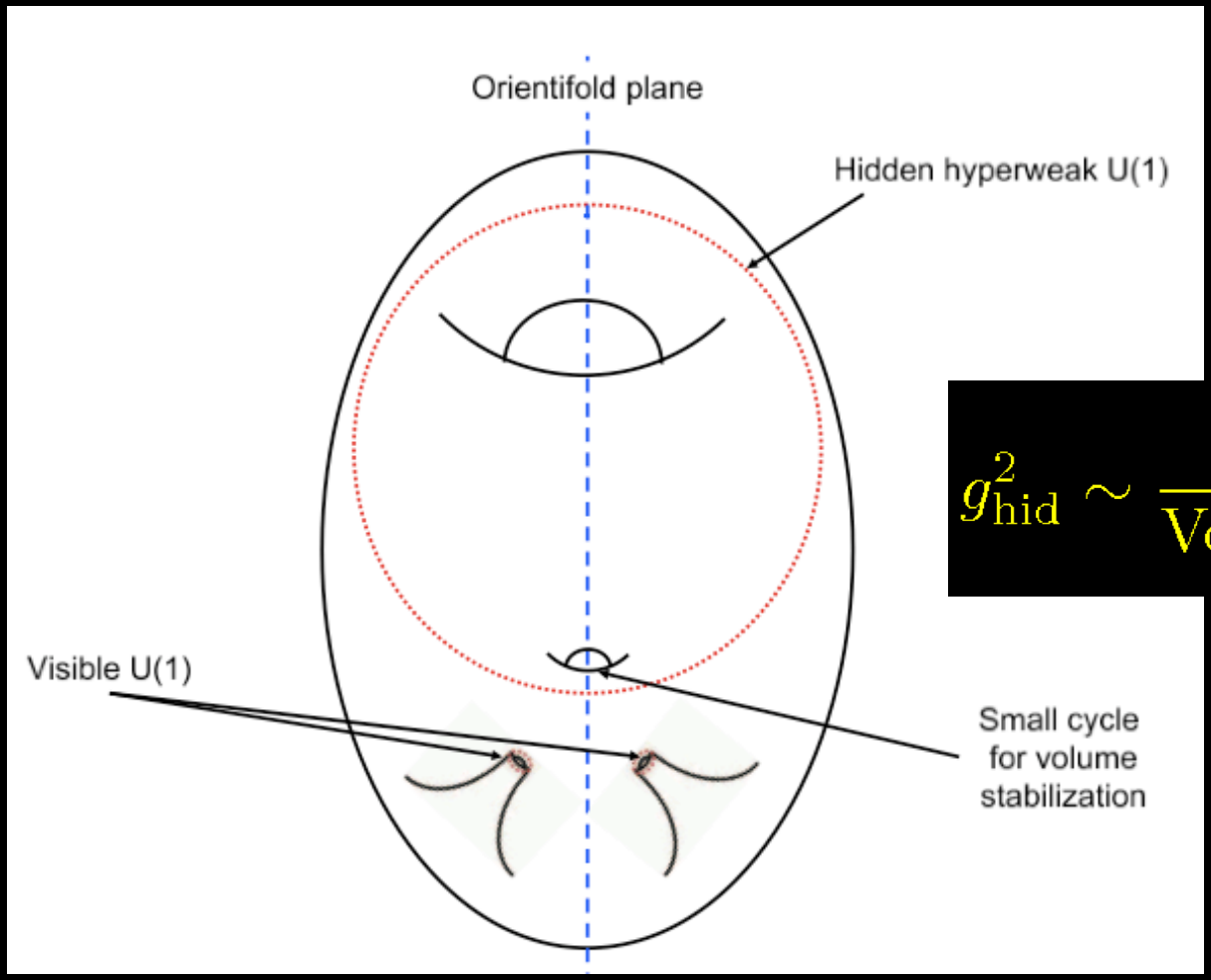

$$g^2_{\rm hid} \sim \frac{2\pi g_s}{\rm Volume^x} \sim \left(\frac{M_s^2}{M_P^2}\right)^x \ll 1$$

$$\chi \sim \frac{g_{\rm vis} g_{\rm hid}}{16\pi^2} \sim \frac{2\pi g_s}{\rm Volume^{x/2}} \sim \left(\frac{M_s^2}{M_P^2}\right)^{x/2} \ll 1$$

Masses

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- Higgs and Stueckelberg mechanism possible

- Example: Stueckelberg

$$(m_{\gamma'}^{\mathrm{Stueck}})^2 \simeq \frac{g_s}{2}\left(\frac{4\pi}{g_s^2}\frac{M_s^2}{M_P^2}\right)^z$$

$$\simeq \frac{g_s}{2}\frac{M_s}{\mathrm{Volume}^z}, \qquad z = \frac{1}{3}, 1.$$

Hidden Photons, All over the place

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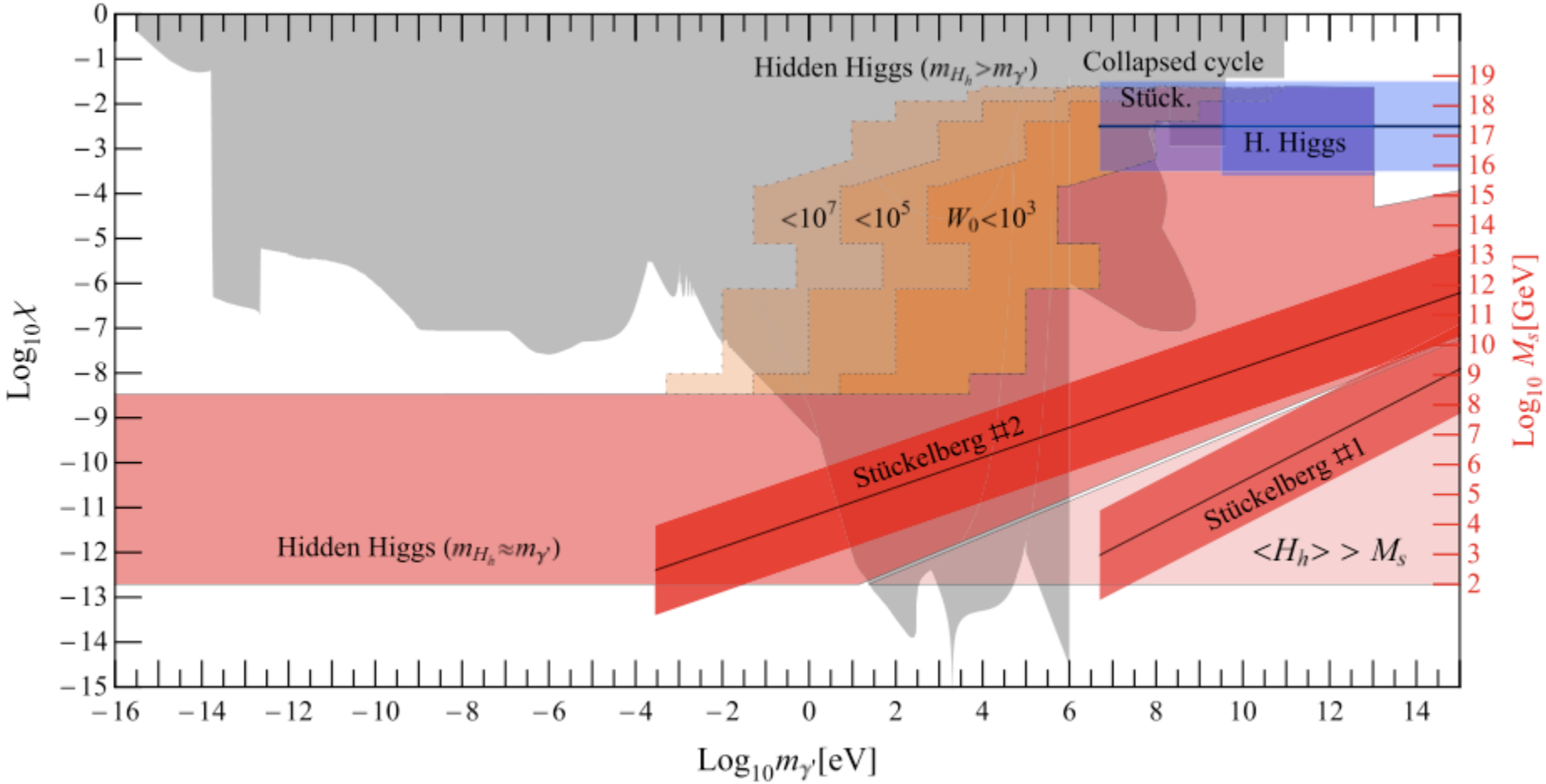

Hidden Photons: Back to Experiment

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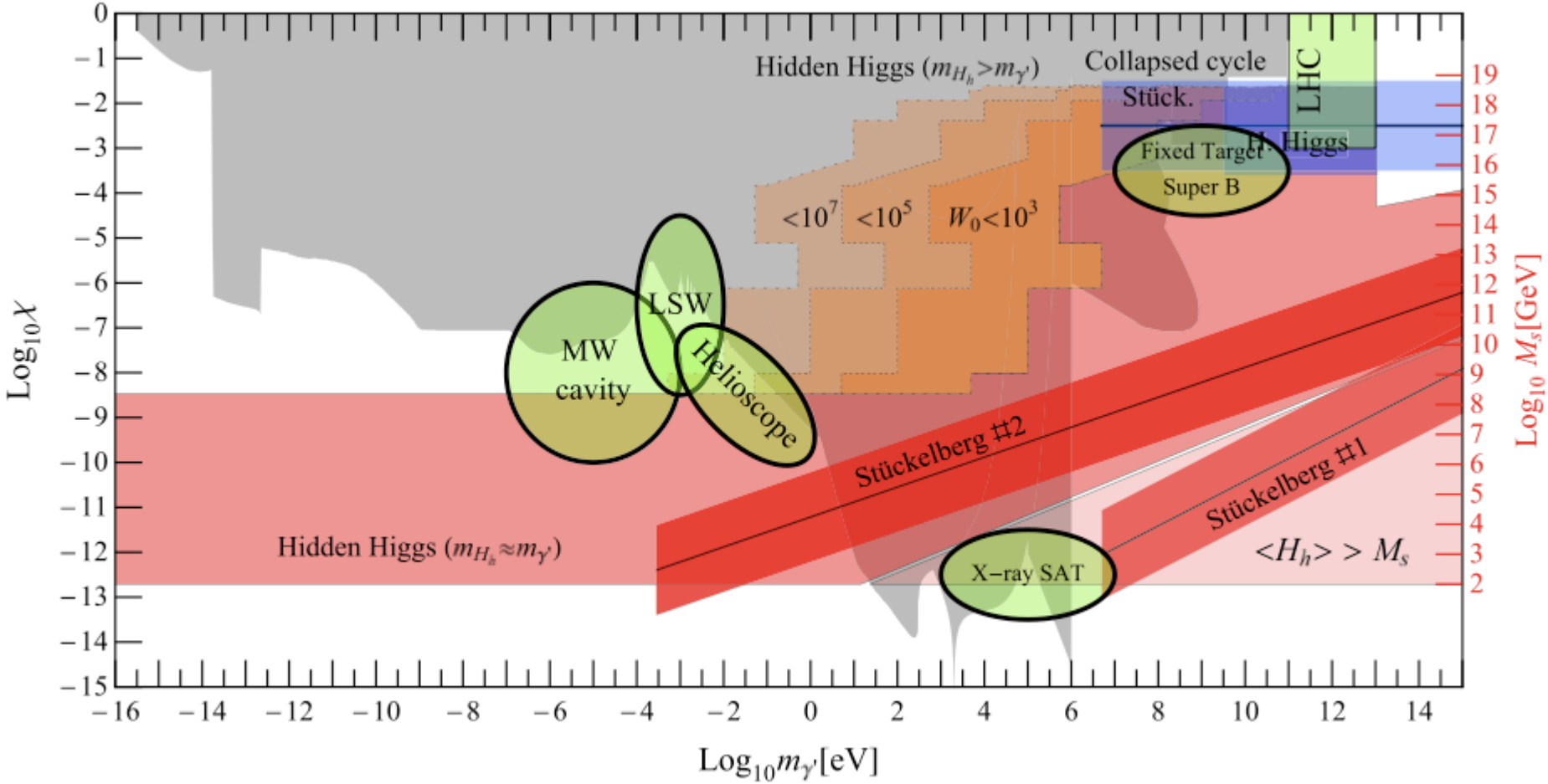

String theory likes extra matter

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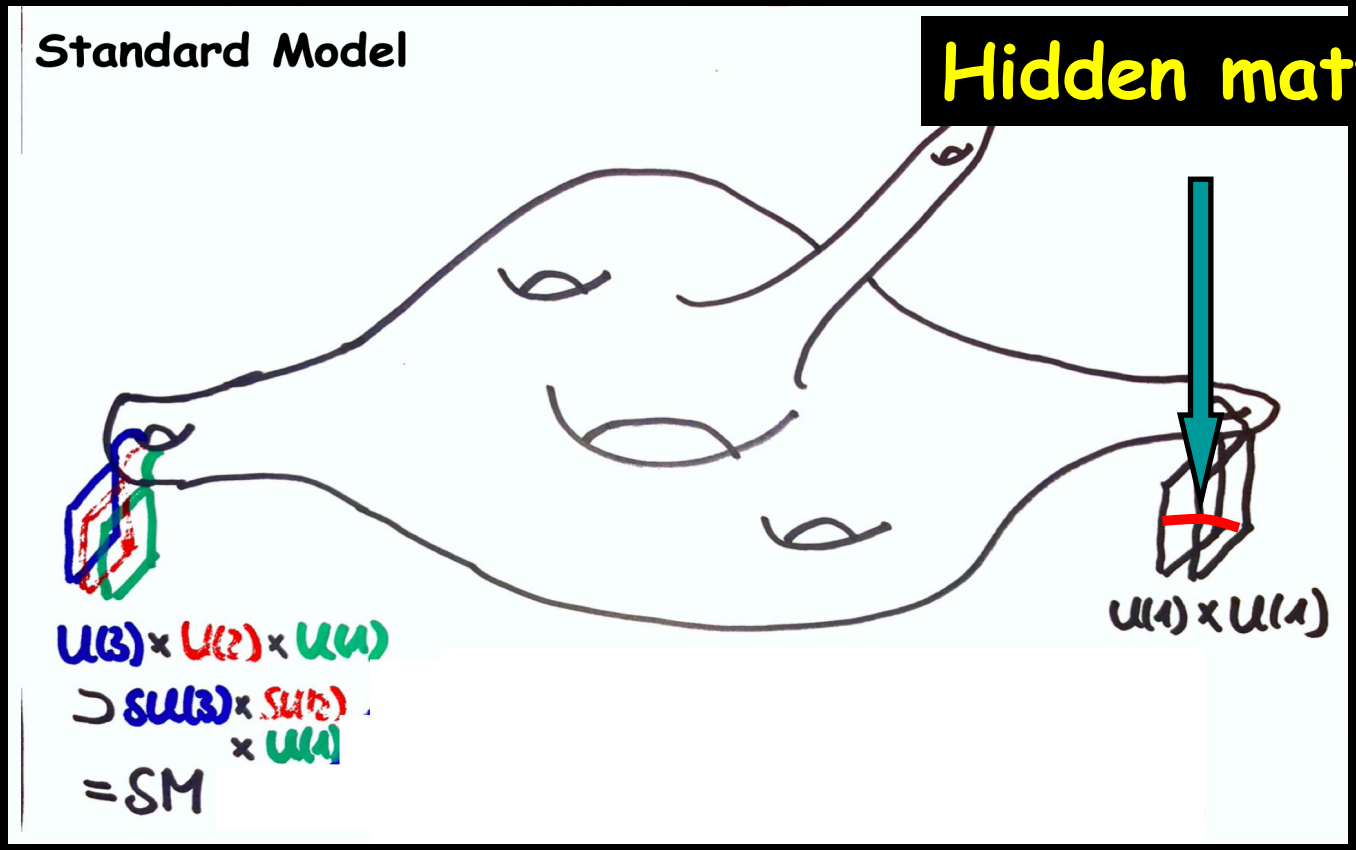

➡ Hidden sector matter

➡ Appears to be minicharged

How coupled?

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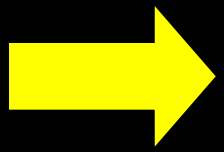
- Kinetic mixing

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F^{\mu\nu}_{(\text{A})} F_{(\text{A})\mu\nu} - \frac{1}{4} F^{\mu\nu}_{(\text{B})} F_{(\text{B})\mu\nu} + \frac{\chi}{2} F^{\mu\nu}_{(\text{A})} F_{(\text{B})\mu\nu},$$

„Our" U(1) | „Hidden" U(1) | Mixing

+ Matter $\mathcal{L}_{\text{int}} = g_{\text{hid}} \bar{h} \gamma_\mu X^\mu h$



Particles with small electric charges
If X is massive it's DM + massive vector

Minicharged particles…

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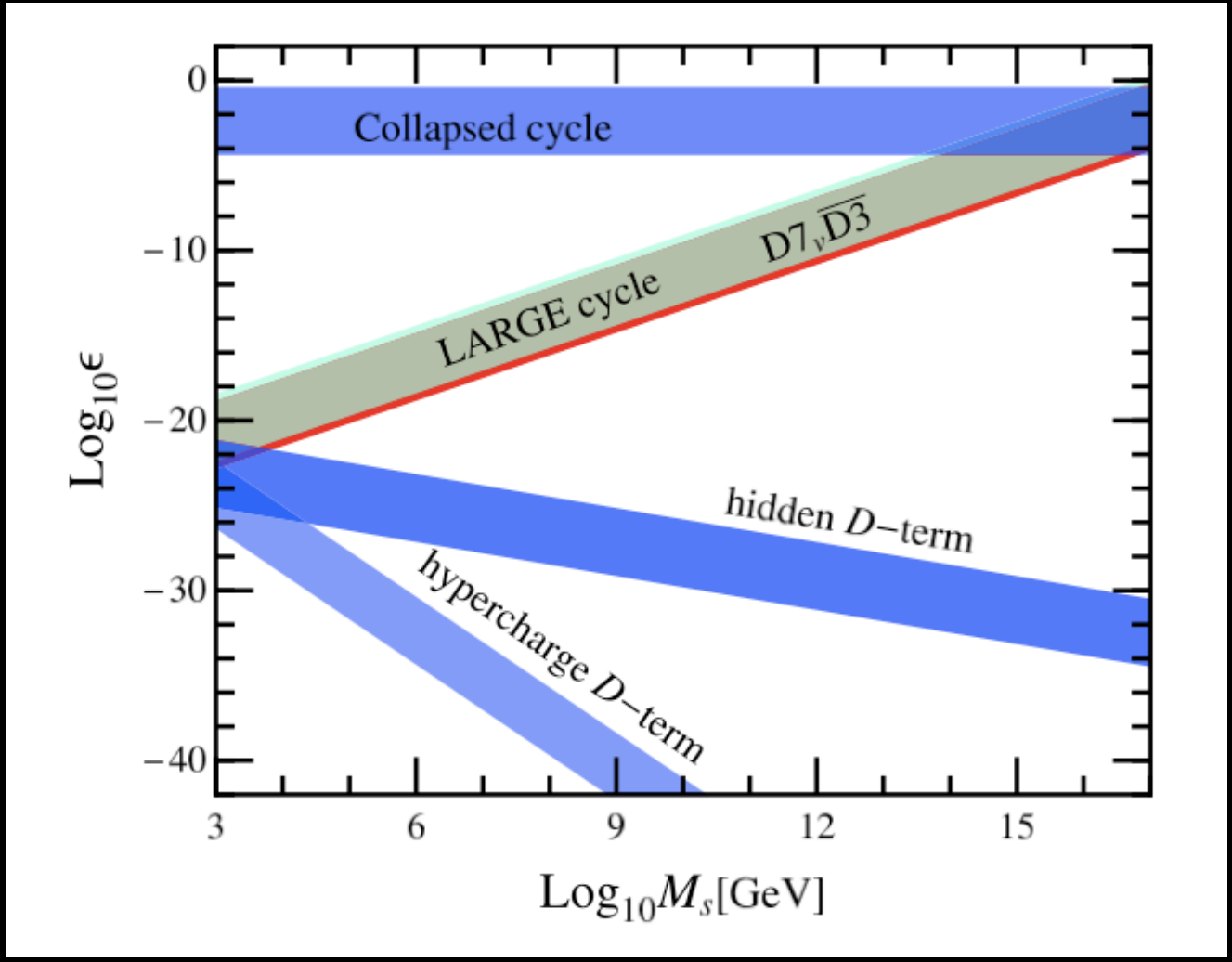

Conclusions

Conclusions

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- Experiments and Observations suggest the existence of a "Dark Sector"

  ➔ Very weakly coupled particles
- Theory allow us to have very weakly coupled particles that are also light!

Examples: Axion(-like particles)

Hidden/dark photons

Conclusions

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Columbus' Theory: Tenerife – Jakarta ~ 3000 miles
Actual distance: ~ 7300 miles

https://spectrum.ieee.org/tech-talk/at-work/test-and-measurement/columbuss-geographical-miscalculations

Lesson:
Theory doesn't have to be correct
in order to find something ;-).
➔Go Explore + Be prepared
for surprises

https://en.wikipedia.org/wiki/Christopher_Columbus#/media/File:Emanuel_Gottlieb_Leutze_-_Columbus_Before_the_Queen.JPG